Available online at www.sciencedirect.com
SCIENCE @ DIRECT®

Soil & Tillage Research 83 (2005) 120–147

Soil & Tillage Research

www.elsevier.com/locate/still

Review

Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA

A.J. Franzluebbers *

US Department of Agriculture, Agricultural Research Service, 1420 Experiment Station Road, Watkinsville, GA 30677-2373, USA

Received 18 March 2004; received in revised form 19 January 2005

Abstract

Agriculture in the southeastern USA can be highly productive (i.e., high photosynthetic fixation of atmospheric CO_2) due to warm-moist climatic conditions. However, its impacts on greenhouse gas emissions and mitigation potential have not been thoroughly characterized. This paper is a review and synthesis of literature pertaining to soil organic C (SOC) sequestration and greenhouse gas emissions from agricultural activities in the southeastern USA. Conservation tillage is an effective strategy to regain some of the SOC lost following decades, and in some areas centuries, of intensive soil tillage and erosion. With conventional tillage (CT) as a baseline, SOC sequestration with no tillage (NT) was 0.42 ± 0.46 Mg ha^{-1} year^{-1} (10 ± 5 years). Combining cover cropping with NT enhanced SOC sequestration (0.53 ± 0.45 Mg ha^{-1} year^{-1}) compared with NT and no cover cropping (0.28 ± 0.44 Mg ha^{-1} year^{-1}). By increasing cropping system complexity, SOC could be increased by 0.22 Mg ha^{-1} year^{-1}, irrespective of tillage management. Taking into account an average C cost of producing and transporting N fertilizer, SOC sequestration could be optimized at 0.24 Mg ha^{-1} year^{-1} with application of 107 kg N ha^{-1} year^{-1} on N-responsive crops, irrespective of tillage management. In longer-term studies (5–21 years), poultry litter application led to SOC sequestration of 0.72 ± 0.67 Mg ha^{-1} year^{-1} (17 ± 15% of C applied). Land that was previously cropped and converted to forages sequestered SOC at a rate of 1.03 ± 0.90 Mg ha^{-1} year^{-1} (15 ± 17 years). Limited data suggest animal grazing increases SOC sequestration on upland pastures. By expanding research on SOC sequestration into more diverse pasture and manure application systems and gathering much needed data on methane and nitrous oxide fluxes under almost any agricultural operation in the region, a more complete analysis of greenhouse gas emissions and potential mitigation from agricultural management systems would be possible. This information will be necessary for developing appropriate technological and political solutions to increase agricultural sustainability and combat environmental degradation in the southeastern USA.

Keywords: Conservation tillage; Cover crop; Grazing; Land use; Manure; Nitrogen fertilization; Pasture

* Tel.: +1 706 769 5631; fax: +1 706 769 8962.
E-mail address: afranz@uga.edu

0167-1987/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2005.02.012

Contents

1. Climatic conditions

The southeastern USA is a region of North America that is generally warm and moist. The boundary of this region is defined for this paper according to an ecoregion concept (Bailey, 1995), originally utilized by the US Forest Service. The region encompasses the southern portion of the humid temperate domain (Bailey, 1995), with a western boundary in central Texas and a northern boundary through central Arkansas, the northern limits of Mississippi and Alabama, and along the eastern edge of the Appalachian mountains to Maryland and Delaware (Fig. 1). Within the region, temperature is generally coldest in the north and warmest in the south and precipitation is wettest in the middle and driest on the western edge (Fig. 2). With the exception of the western and southern fringes, precipitation tends to exceed potential evapotranspiration (PET) throughout the region. Seasonal differences in temperature and precipitation occur among locations within the region (Fig. 3).

2. Soils and land use characteristics

Soils of the region vary widely and include Alfisols, Entisols, Histosols, Inceptisols, Mollisols, Spodosols, Ultisols, and Vertisols (Table 1). Most soils of the region have an udic moisture regime and lie within the hyperthermic, thermic, and upper mesic temperature regimes.

Land resources in the region (USDA-SCS, 1981) include portions of the southwestern prairies, cotton, and forages (J), east and central general farming and forestry (N), Mississippi delta cotton and feed grains (O), south Atlantic and gulf slope cash crop, forest, and livestock (P), Atlantic and gulf coast lowland forest and truck crop (T), and Florida subtropical fruit, truck crop, and range (U) (Table 1).

Total land area in the region is 129 Mha (14% of the USA), of which 20% was in crop land and 15% was in pasture land in 1997 (Fig. 4). Significant variations in agricultural land use occurred among provinces within the region, with the Lower Mississippi Riverine province having the highest percentage of land in

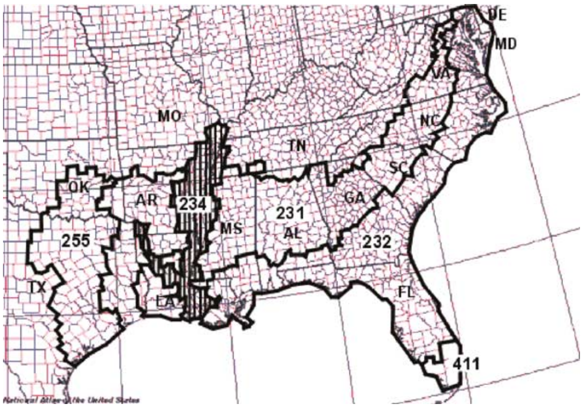

Fig. 1. Geographical illustration of the southeastern USA and the five ecoregion provinces (255 is Prairie Parkland, 234 is Lower Mississippi Riverine, 231 is Southern Mixed Forest, 232 is Outer Coastal Plain, and 411 is Everglades).

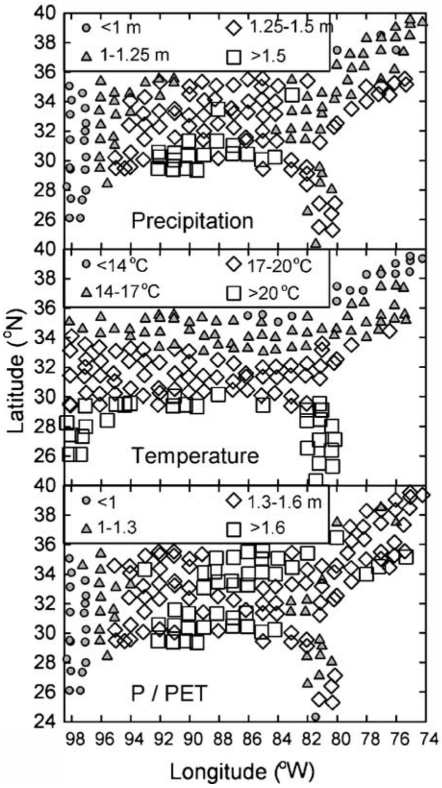

Fig. 2. Geographical distribution of mean annual precipitation, mean annual temperature, and the ratio of mean annual precipitation-to-mean annual potential evapotranspiration (P/PET) in the southeastern USA. Data of mean annual temperature and precipitation from selected locations on ~ 1° grid from the National Climatic Data Center, with calculations of PET based on the Thornthwaite equation (courtesy Deborah Abrahamson).

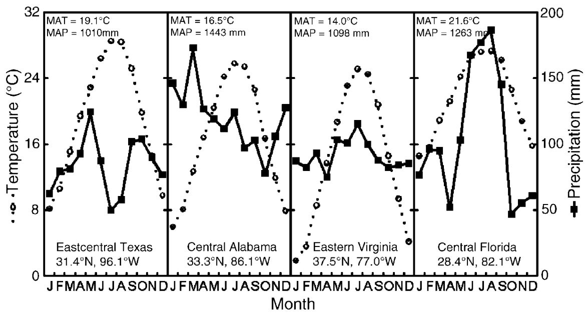

Fig. 3. Mean monthly temperature and precipitation for four locations within the southeastern USA. Data from National Climatic Data Center.

crops (49%) and the Prairie Parkland having the highest percentage in pastures (54%). Land area not in agricultural use is mainly in managed and unmanaged forest, coastal wetland, federally owned land, and urban development.

Distribution of agricultural land use within a province was not uniform (Fig. 5). The middle two quartiles of counties (i.e. the middle 50% of observations in ranked order) had 24–35% crop land in the Prairie Parkland province, 23–68% crop land in the Lower Mississippi Riverine province, 8–18% crop land in the Southern Mixed Forest province, 6–26% crop land in the Outer Coastal Plain province, 1–5% cropland in the Everglades province, and 9–27% cropland for the entire southeastern USA. Half of the counties had 45–64% pasture land in the Prairie Parkland province, 1–6% pasture land in the Lower Mississippi Riverine province, 6–14% pasture land in the Southern Mixed Forest province, 2–9% pasture land in the Outer Coastal Plain province, 1–3% pasture land in the Everglades province, and 4–16% pasture land for the entire southeastern USA.

During the past century, the southeastern USA has undergone many changes in the characteristics of agricultural production (state-level composites from the 11 states dominantly represented in the region, including Alabama, Arkansas, Delaware, Florida, Georgia, Louisiana, Maryland, Mississippi, North Carolina, South Carolina, and Virginia) (USDA-NASS, 1997). Farmland area peaked in 1950

Table 1
Ecoregion provinces and portions of land resource regions, major land resource areas, and dominant soils contained within

Ecoregion province	Land resource region	Major land resource area	Dominant soils
231: Southern mixed forest	N: east and central farming and forest	128: Southern Appalachian ridges and valleys	Udults, Ochrepts
		129: Sand Mountain	
	P: South Atlantic and gulf slope cash crops, forest, and livestock	133: Southern coastal plain	Udults, Udalfs, Ochrepts
		134: Southern Mississippi valley silty uplands	
		135: Alabama and Mississippi Blackland Prairies	
		136: Southern Piedmont	
	S: Northern Atlantic slope diversified farming	148: Northern Piedmont	Udults, Udalfs, Ochrepts
232: Outer coastal plain	P: South Atlantic and gulf slope cash crops, forest, and livestock	133: Southern coastal plain	Udults, Udalfs, Psamments
		134: Southern Mississippi valley silty uplands	
		137: Carolina and Georgia sand hills	
		138: North-central Florida ridge	
	T: Atlantic and gulf coast lowland forest and crop	150: Gulf coast prairies	Uderts, Aquents, Aqualfs, Aquolls, Aquepts, Saprists, Hemists, Aquults, Aquods, Udalfs, Udults
		151: Gulf coast marsh	
		152: Gulf coast flatwoods	
		153: Atlantic coast flatwoods	
	U: Florida subtropical fruit, truck crop, and range	154: South central Florida ridge	Psamments, Udults, Aquods, Aquents, Aquepts, Saprists, Fibrists, Aqualfs, Aquolls
		155: Southern Florida flatwoods	
		156: Florida everglades and associated areas	
234: Lower Mississippi riverine	O: Mississippi delta cotton and feed grains	131- Southern Mississippi valley alluvium	Aquepts, Aqualfs, Aquents, Udolls, Udalfs,
	P: South Atlantic and gulf slope cash crops, forest, and livestock	134: Southern Mississippi valley silty uplands	Udalfs
255: Prairie parkland	J: Southwestern prairies cotton and forage	84: Cross timbers	Ustalfs, Ochrepts, Ustolls, Usterts, Ochrepts, Aqualfs
		85: Grand prairie	
		86: Texas blackland prairie	
		87: Texas claypan area	
	P: South Atlantic and gulf slope cash crops, forest, and livestock	133: Southern coastal plain	Udults
	T: Atlantic and gulf coast lowland forest and crop	150: Gulf coast prairies	Uderts, Aqualfs, Aquents, Aquolls, Aquepts
411: Everglades	U: Florida subtropical fruit, truck crop, and range	156: Florida everglades and associated areas	Saprists, Fibrists, Aqualfs, Aquolls, Aquods

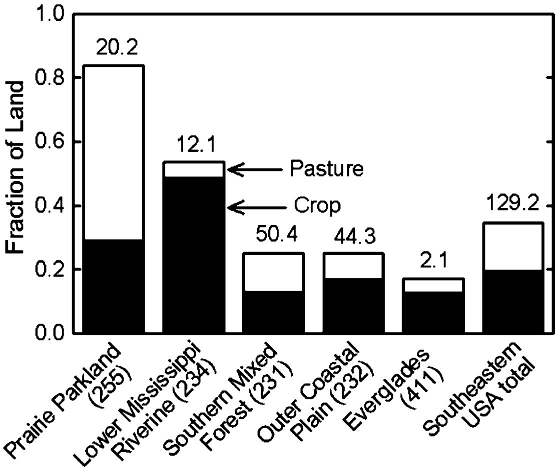

Fig. 4. Fraction of land in crops and pasture as affected by ecoregion province within the southeastern USA. Value above bar represents total land area (Mha). Data from USDA-NASS (1997).

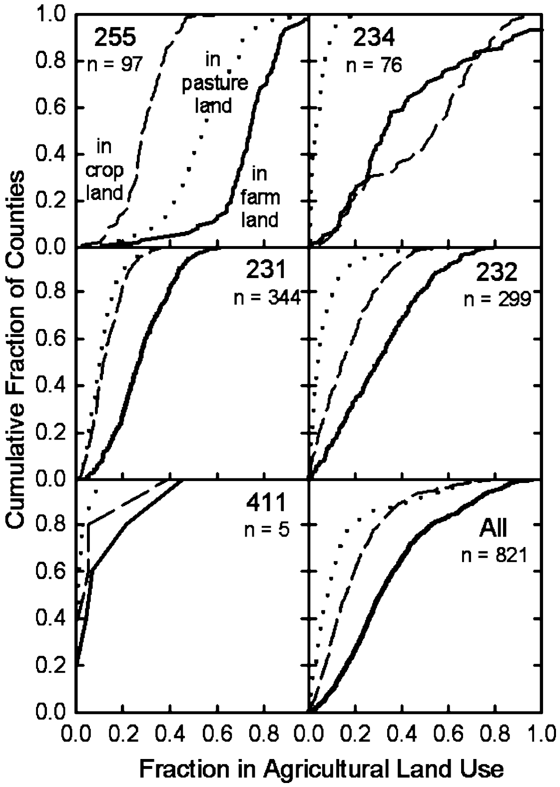

Fig. 5. Frequency distribution of agricultural land use among counties in five ecoregion provinces [255 = Prairie Parkland, 234 = Lower Mississippi Riverine, 231 = Southern Mixed Forest, 232 = Outer Coastal Plain, and 411 = Everglades] and across all of the southeastern USA. Data from USDA-NASS (1997).

(67 Mha, 60% of total land area) (Fig. 6). However since that time, farmland in the region has declined by an average of 0.72 Mha year^{-1}. Crop land peaked in 1945 (24% of total land area) and has declined an average of 0.11 Mha year^{-1} since that time. From the 1997 census of agriculture, the region had 31% of the land area in farms and 18% as crop land. The agricultural profile in the southeastern USA has changed from corn and cotton dominating crop production in the early part of the 20th century to those crops as minor components later in the century (Fig. 6). Concerning livestock, agriculture in the southeastern USA shifted towards more cattle, fewer sheep, a gradual decline with a recent resurgence (especially in North Carolina) in swine, and an exponential rise in broiler production (Fig. 6).

Proportional to the land area it contained, the 11-state region has had average to above average agricultural production characteristics compared with the entire USA. Cattle and hog inventories have been similar to the USA average. Crop and livestock sales averaged 18% of the total for the USA, which was above the proportion of land area for the region (12%). Fertilizer purchased has been declining recently, but still remains above the per total land area average. One-third of the layer chickens and 78% of the broiler chickens produced in the USA have come from the 11-state region in the southeastern USA. The region produces a variety of crop products (Table 2), specializing in sugarcane, sweet potato, peanut, rice, tobacco, cotton, nursery sales, orchards, rye, and vegetables.

3. Management impacts on soil organic C (SOC)

3.1. Land use

The warm-moist climatic conditions of the southeastern USA are conducive for high annual C fixation in plant biomass, but also for high rates of decomposition. Upland soils of the region typically contain 40–120 Mg ha^{-1} of organic C to a depth of 1 m (USDA-NRCS, 1997). Poorly drained soils along coastal areas contain in excess of 120 Mg ha^{-1} of organic C due to reduced rate of decomposition,

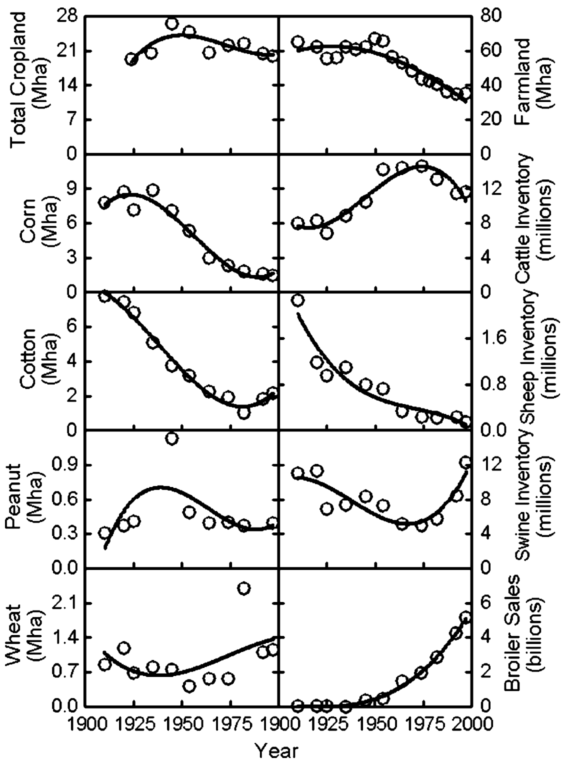

Fig. 6. Agricultural production characteristics of selected crops and livestock during the past 100 years for 11 states in the southeastern USA, including Alabama, Arkansas, Delaware, Florida, Georgia, Louisiana, Maryland, Mississippi, North Carolina, South Carolina, and Virginia. Data from USDA-National Agricultural Statistics Service publications.

because of poor aeration and subsequent accumulation of organic matter.

With soil disturbance of long-term native vegetation, loss of SOC can be rapid and extensive. A chronosequence of disturbance in the Georgia Piedmont region indicated that SOC to a depth of 20 cm was rapidly lost following disturbance (i.e., 40 Mg ha^{-1} initially and 20 Mg ha^{-1} at the end of 10 years of disturbance), but also rapidly regained upon cessation of disturbance (i.e., 13 Mg ha^{-1} initially and 28 Mg ha^{-1} following 10 years of undisturbed land use) (Fig. 7). With soil disturbance for 50 years, loss of SOC was 65% of that under native condition. These changes are high compared with the rest of the USA and possible because of the relatively high temperature and abundant precipitation in the region that facilitate decomposition and erosion. In the relatively cold region of Canada, loss of SOC was 24 $\pm$ 6% of that under native vegetation (VandenBygaart et al., 2003). From locations around the world, SOC losses following cultivation of native forests or grasslands were estimated at 20% (Mann, 1986). From a global set of 56 comparisons, with more than half from Mollisols of the North American grassland region, SOC loss varied from 24 to 43% of that under native vegetation, depending upon sampling depth (Davidson and Ackerman, 1993).

The southeastern USA has experienced enormous soil erosion during the 19th and 20th centuries. Estimates of soil loss in the region include rates of (1) 18 Mg ha^{-1} year^{-1} under inversion tillage and 3 $\pm$ 2 Mg ha^{-1} year^{-1} under conservation tillage in southern Mississippi (McGregor et al., 1975), (2) 28 $\pm$ 29 Mg ha^{-1} year^{-1} under inversion tillage, 13 $\pm$ 15 Mg ha^{-1} year^{-1} with grass buffers and terraces, and 0.1 $\pm$ 0.1 Mg ha^{-1} year^{-1} under native forestland in northern Mississippi (Harden et al., 1999a,b), and (3) 23 Mg ha^{-1} year^{-1} under 2.5 years of inversion tillage and 0.04 Mg ha^{-1} year^{-1} under conservation tillage in northern Georgia (Endale et al., 2000). Soil erosion is particularly detrimental to the stock of SOC, since it is (1) typically most concentrated in surface soil and (2) lighter than mineral soil, and therefore, preferentially transported as particulate matter in sediment (Lowrance and Williams, 1988). Even if eroded sediment from fields in conservation tillage were higher in SOC concentration than from fields with inversion tillage, the higher rate of soil loss with inversion tillage would usually lead to greater SOC loss (Schreiber and McGregor, 1979).

Soils found widely throughout the southeastern USA under forest typically have SOC concentrations $>$10 g kg^{-1} near the surface, but concentrations often $<$5 g kg^{-1} below 0.5 m depth (Fig. 8). Soil organic C concentration declines with depth in a logarithmic manner. Land under cropping almost always has lower SOC concentration than under forest or grass. Stimulation of organic matter decomposition occurs during cultivation due to frequent tillage, which releases organic matter protected in aggregates and redistributes organic matter in the soil profile where environmental conditions are more favorable for decomposition.

From a compilation of studies comparing at least two land uses, SOC content under grass was not

Table 2
Crop production characteristics of the southeastern USA in 1997 (11-state region including Alabama, Arkansas, Delaware, Florida, Georgia, Louisiana, Maryland, Mississippi, North Carolina, South Carolina, and Virginia) (USDA-NASS, 1997)

Crop enterprise	Production in the southeastern USA	Percentage of total for USA	Leading state in region
Sugarcane (*Saccharum officinarum* L.)	25.3 Tg	89	Florida
Hay	12.0 Tg	9	Arkansas
Corn grain (*Zea mays* L.)	9.2 Tg	4	North Carolina
Soybean [*Glycine max* (L.) Merr.]	8.0 Tg	12	Arkansas
Rice (*Oryza sativa* L.)	5.4 Tg	65	Arkansas
Corn silage	5.3 Tg	7	Virginia
Wheat (*Triticum aestivum* L.)	3.8 Tg	6	Arkansas
Cotton lint (*Gossypium hirsutum* L.)	1.8 Tg	46	Georgia
Peanut (*Arachis hypogaea* L.)	1.1 Tg	71	Georgia
Grass silage	0.8 Tg	3	Virginia
Potato (*Solanum tuberosum* L.)	0.7 Tg	4	Florida
Sorghum grain [*Sorghum bicolor* (L.) Moench]	0.5 Tg	4	Arkansas
Tobacco (*Nicotiana tabacum* L.)	0.5 Tg	61	North Carolina
Sweet potato [*Ipomoea batatas* (L.) Lam.]	0.4 Tg	81	North Carolina
Barley (*Hordeum vulgare* L.)	0.3 Tg	3	Virginia
Sorghum silage	0.1 Tg	3	Georgia
Oat (*Avena sativa* L.)	0.1 Tg	4	North Carolina
Rye (*Secale cereale* L.)	0.03 Tg	23	Georgia
Fescue seed (*Festuca* L.)	0.002 Tg	2	Arkansas
Orchards	0.52 Mha	25	Florida
Vegetables	0.24 Mha	16	Florida
Nursery sales	2.7 billion $	25	Florida

significantly different ($p = 0.20$) from that under forest (Table 3). The percent change in SOC from individual studies varied widely in the forest-grass comparison, sometimes higher and sometimes lower. Soil organic C content under cropping was significantly lower than under grass or forest, with loss of 36 ± 29% compared with forest.

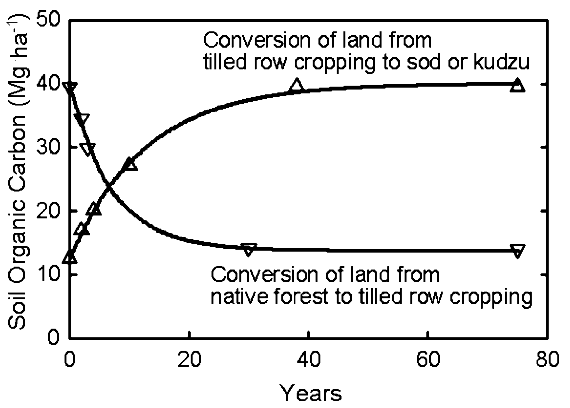

Fig. 7. Soil organic C under two chronosequences of aggradation and degradation in the Georgia Piedmont. Modified from Hendrix et al. (1998). Data from Giddens (1957) and Jones et al. (1966).

3.1.1. *Research evaluation and needs to characterize the effects of land use on SOC sequestration*

In general, available data characterizing SOC under different land uses indicate that once stable vegetative cover is disturbed by cultivation, SOC declines. The extent of decline can be dramatic in the southeastern USA due to favorable conditions for (1) decomposition (relatively high temperature and rainfall), which oxidizes organic matter and (2) water erosion, which carries soil containing organic matter from uplands through riverine systems to lowlands. The extent of soil erosion in the past has been particularly extensive in the southeastern USA (Trimble, 1974). Development of various soil conservation techniques during the latter part of the 20th century has helped to reduce erosion losses considerably.

Although a database on SOC under forest, grass, and crop land uses is available, it is far from comprehensive and not necessarily reflective of current land use conditions. Greater effort is needed

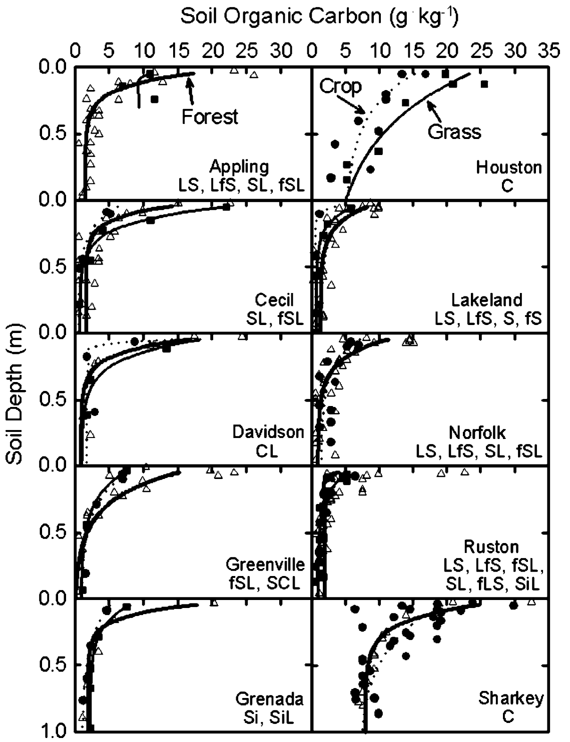

Fig. 8. Soil organic C depth distribution from multiple locations within typical soils of the southeastern USA. Data from McCracken (1959).

to coordinate SOC evaluations between agricultural and forest research communities to develop meaningful land use comparisons on dominant soil types of the region. There is a diversity of forest and grass management variables needing investigation to better characterize SOC under major land uses in the region. The numerous conservation benefits of grass cover, having become increasingly recognized during the latter part of the 20th century in the southeastern USA, should include the potential benefit to the environment through SOC sequestration.

3.2. Tillage

Conservation tillage systems have been extensively studied in the southeastern USA, as exemplified in the popularity of the annual meetings of the Southern Conservation Tillage Conference for Sustainable Agriculture since 1978 (Iversen, 2002). The Conservation Technology Information Center estimates that 42.5% of the cropped land in the southeastern region (defined as AL, FL, GA, KY, MS, NC, SC, TN, and VA) was managed with some form of conservation tillage in 2002 (CTIC, 2002). Thirty-six percent of the crop land was managed with NT or strip tillage in 2002, almost double that of 1992.

3.2.1. Carbon inputs (i.e. crop production)

Although agronomic performance of crops under different tillage systems is evaluated primarily from an economic viewpoint, crop performance can also be used as an indication of net C fixed by plants. Crop residue from above- and below-ground components is an essential input of C for maintaining or building SOC. By increasing cropping intensity to more effectively utilize water and sunlight available for plant growth, more C can potentially be produced for food, as well as for residues, resulting in more C as an input to soil. From a 10-year study in southcentral Texas, estimated C input from crop residues increased linearly with increasing cropping intensity under both conventional and NT (Fig. 9A). Greater C input with increasing cropping intensity led to greater SOC under both tillage systems (Fig. 9B). As a fraction of C input, SOC sequestration was more sensitive to the quantity of C input under CT (Fig. 9C), suggesting that greater water utilization by plant growth during a longer period of the year was important for slowing decomposition of added C input. Under NT, the fraction of C input that was sequestered as SOC was relatively unaffected by cropping intensity, probably because contact of crop residues with surface soil, which harbors heterotrophic microorganisms and retains water, was minimal irrespective of the quantity of residue.

Literature is available concerning the effect of conservation tillage on crop yield in the southeastern USA (Table 4). Sorted by crops, the effect of NT compared with CT on yield was significantly positive for corn stover (18% increase) only. Across studies, there was no effect of tillage on yield for other crops. The modal yield response to NT compared with CT was 0 to 10% for corn and cotton and −10 to 0% for peanut, soybean, and wheat. Across all crops, yield under NT was 6% greater ($p < 0.01$) than under CT. Crop yield would likely benefit from moisture conservation of surface-placed crop residues with NT even in this humid climatic region. Relatively hot

Table 3
Soil organic C content under different long-term land use and percent change from forest land use in the southeastern USA

Location	Soil taxonomy	Soil depth (cm)	Land use [Soil organic C ($Mg\ ha^{-1}$)]			Change from forest to (%)		Reference
			Forest	Grass	Crop	Grass	Crop	
Renner TX	Oxyaquic Hapludert	30	ND	82.9	46.6	ND	ND	Laws and Evans (1949)
Renner TX	Oxyaquic Hapludert	30	ND	91.9	65.1	ND	ND	Laws and Evans (1949)
Renner TX	Oxyaquic Hapludert	30	ND	56.7	54.9	ND	ND	Laws and Evans (1949)
NC, SC, VA	Typic Kanhapludult	25	34.7	33.4	ND	−4	ND	McCracken (1959)
AL, NC, SC, VA	Typic Kanhapludult	25	28.4	43.1	16.2	52	−43	McCracken (1959)
GA, SC, VA	Rhodic Kandiudult	25	33.3	39.5	19.9	19	−40	McCracken (1959)
AL, FL, GA	Rhodic Kandiudult	25	37.1	19.8	21.9	−47	−41	McCracken (1959)
MS	Oxyaquic Fraglossudalf	25	32.8	21.8	15.7	−34	−52	McCracken (1959)
AL, AR, MS	Oxyaquic Hapludert	25	ND	60.4	42.7	ND	ND	McCracken (1959)
AL, AR, FL, MS, TX	Typic Quartzipsamment	25	20.9	15.0	6.2	−28	−70	McCracken (1959)
AL, FL, MS, SC, VA	Typic Kandiudult	25	27.1	ND	19.8	ND	−27	McCracken (1959)
AL, AR, FL, MS, SC, TX	Typic Paleudult	25	9.9	14.4	14.5	45	47	McCracken (1959)
AR, LA, MS	Chromic Epiaquert	25	54.7	ND	52.4	ND	−4	McCracken (1959)
Holly Springs MS	Oxyaquic Fraglossudalf	30	45.2	ND	17.9	ND	−60	Rhoton and Tyler (1990)
Temple, TX	Oxyaquic Hapludert	30	ND	91.4	59.0	ND	ND	Potter et al. (1999)
Burleson TX	Oxyaquic Hapludert	30	ND	92.5	50.8	ND	ND	Potter et al. (1999)
Riesel TX	Oxyaquic Hapludert	30	ND	111.7	67.6	ND	ND	Potter et al. (1999)
Watkinsville GA	Typic Kanhapludult	20	48.1	37.8	26.5	−21	−45	Franzluebbers et al. (2000b)
Eastern MD	Typic Hapludult	15	ND	32.3	12.3	ND	ND	Islam and Weil (2000)
Eastern MD	Inceptic Hapludult	15	ND	24.6	15.1	ND	ND	Islam and Weil (2000)
Eastern MD	Fluvaquentic Dystrudept	15	ND	31.0	18.7	ND	ND	Islam and Weil (2000)
Eastern MD	Typic Hapludult	15	ND	19.3	18.2	ND	ND	Islam and Weil (2000)
Central MD	Typic Hapludult	15	ND	48.9	28.4	ND	ND	Islam and Weil (2000)
Central MD	Aquic Hapludult	15	ND	36.8	30.1	ND	ND	Islam and Weil (2000)
Crossville AL	Typic Hapludult	20	58.8	27.7	31.0	−53	−47	Fesha et al. (2002)
Shorter AL	Typic Paleudult	20	32.1	35.3	25.1	10	−22	Fesha et al. (2002)
Central AL	Vertic Epiaquept	30	81.3	86.1	44.2	6	−46	Torbert et al. (2004)
Central AL	Grossarenic Paleudult	30	68.9	44.6	35.0	−35	−49	Torbert et al. (2004)
Mean ± S.D.		24 ± 6	49.9a	47.4a	31.1b	−8 ± 35	−36 ± 29	

Land use means followed by the same letter are not significantly different at $p = 0.05$.
ND, not determined.

conditions in the summer, despite an overall abundance of precipitation, create high evaporative demand such that preservation of soil moisture with surface residues is vitally important for increasing productivity.

A number of tillage studies in the southeastern USA have been conducted for >5 years and they have revealed important information on changes with time in (1) relative yield and (2) the need for N fertilizer to achieve optimum yield. From a group of 11 tillage studies, relative yield of various crops under NT compared with CT increased logarithmically ($p < 0.01$) with time from a starting point of 0.94, which was not significantly different from unity (Fig. 10A). Data from Texas suggest that N fertilizer required to achieve 95% maximum sorghum grain yield with NT would be initially 60% higher than with CT (Fig. 10B). With time, however, the N fertilizer requirement declined linearly ($p = 0.06$), such that after 12 years of continuous NT, N fertilizer requirement would be similar to that with CT. Both relative yield and N fertilizer requirement responses to long-term NT suggest that SOC accumulation could lead to either (1) greater yield potential with similar N fertilizer input or (2) similar yield with reduced N fertilizer input.

3.2.2. Soil organic C stock

In a number of studies in the southeastern USA, SOC under conservation tillage (mostly NT) has been

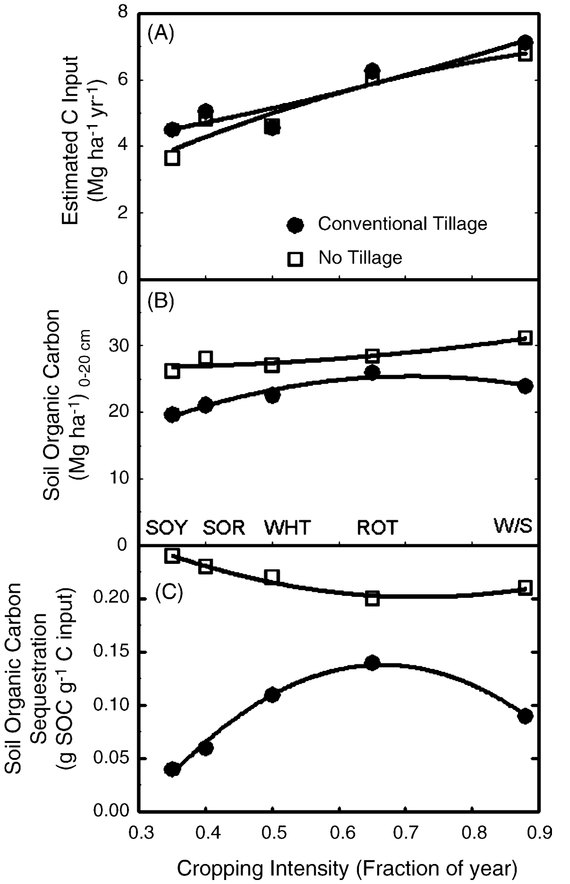

Fig. 9. Estimated C input (A), soil organic C content (B), and soil organic C sequestration (C) under conventional and no tillage as a function of cropping intensity. SOY is continuous soybean, SOR is continuous sorghum, WHT is continuous wheat, ROT is sorghum-wheat/soybean, and W/S is wheat/soybean. Data from Franzluebbers et al. (1998).

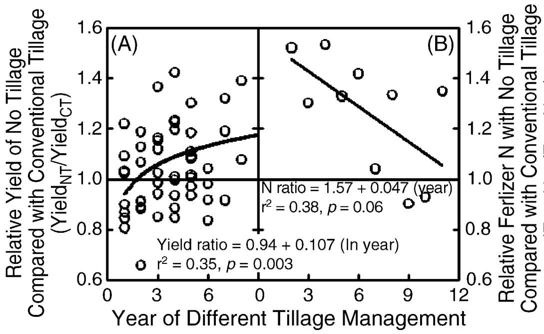

Fig. 10. Changes with time in relative yield (A) and relative N fertilizer N requirement to achieve 95% of maximum yield (B) with no tillage compared with conventional tillage. Data in Panel A represent corn grain yield from Karlen et al. (1989); cotton seed yield from Burmester et al. (1993, 2002), Dabney et al. (1993), Triplett et al. (1996), Nyakatawa and Reddy (2002), and Schwab et al. (2002); cotton lint yield from Hutchinson et al. (1993); and sorghum grain yield from Langdale et al. (1990) and Dabney et al. (1993). Data in panel B were derived for sorghum grain yield reported in Franzluebbers et al. (1995a).

compared to that with some form of CT (inversion tillage that leaves the surface with <30% residue cover). For those studies with SOC concentration reported without bulk density or calculation of SOC content on a volumetric basis, bulk density was predicted from the non-linear relationship with SOC concentration according to:

$$BD = 0.3 + 1.28\,e^{-0.018SOC}$$

where, BD is bulk density (Mg m^{-3}) and SOC is soil organic C (g kg^{-1}) from 230 observations in a pasture experiment in Georgia at four depth intervals to 30 cm (Schnabel et al., 2001). Accuracy of this predicted bulk density on SOC content could be evaluated from six studies in Alabama, Mississippi, and eastern Texas where bulk density was reported separately (Fig. 11). Although prediction of bulk density did not correspond tightly to measured data, the majority of comparisons were within ±0.2 Mg m^{-3} (Fig. 11A), which resulted in a very close relationship between predicted and measured SOC on a volumetric basis (Fig. 11B).

From a compilation of 35 literature citations involving 96 comparisons of tillage systems at 22 locations in seven states of the southeastern USA, SOC was 25.2 ± 11.6 Mg ha^{-1} under CT and 28.5 ± 11.3 Mg ha^{-1} under NT (Table 5). More than 90% of the observations had SOC greater under NT than CT. The mean and median difference in SOC between conventional and NT was 0.42 and 0.30 Mg ha^{-1} $year^{-1}$, respectively, during 10 ± 5 years of evaluation. Half of the observations (i.e., the middle 50% of observations in ranked order) ranged from 0.13 to 0.62 Mg ha^{-1} $year^{-1}$. These estimates of SOC sequestration with NT are similar to other estimates comparing conservation tillage with CT within various domains. For the USA, Lal et al. (1998) assumed an average value of 0.5 Mg ha^{-1} $year^{-1}$ for SOC sequestration with NT, mulch tillage, and ridge tillage. VandenBygaart et al. (2003)

Table 4
Crop yield (Mg ha^{-1}) as affected by tillage system (CT is conventional tillage and NT is no tillage) in the southeastern USA

Crop type	Soil order	Number of pairs	CT	NT	Probability > t
Corn grain[a]	Alfisols, Mollisols, Ultisols, Vertisols	19	6.82	7.12	0.14
Corn silage[b]	Ultisols	5	15.34	16.10	0.33
Corn stover[c]	Ultisols, Vertisols	3	7.40	8.76	0.04
Cotton lint[d]	Alfisols, Ultisols, Vertisols	18	1.04	1.06	0.44
Cotton seed[e]	Alfisols, Ultisols, Vertisols	9	2.59	2.69	0.08
Peanut seed[f]	Inceptisols, Ultsols	6	3.37	3.43	0.64
Sorghum grain[g]	Alfisols, Inceptisols, Ultisols, Vertisols	8	4.48	4.34	0.75
Soybean seed[h]	Alfisols, Inceptisols, Ultisols, Vertisols	18	2.05	2.12	0.42
Wheat grain[i]	Alfisols, Inceptisols, Ultisols, Vertisols	9	3.00	3.11	0.72
Mean		95	5.12	5.41	0.001

[a] Corn grain data from Cassel and Wagger (1996), Edwards et al. (1988), Gallaher (1993), Hargrove (1985), Karlen and Sojka (1985), Karlen et al. (1989), Meisinger et al. (1985), Mitchell et al. (2002), Mullins et al. (1998), Nyakatawa and Reddy (2002), Parsch et al. (2001), Raczkowski et al. (2002), Richardson and King (1995), Smart and Bradford (1999), Torbert et al. (2001), Triplett et al. (2002), and Wagger and Denton (1989, 1992).

[b] Corn silage data from Cassel and Wagger (1996), Meisinger et al. (1985), Mullins et al. (1998), Nelson et al. (1977), and Sainju and Singh (2001).

[c] Corn stover data from Hargrove (1985), Nyakatawa and Reddy (2002), and Torbert et al. (2001).

[d] Cotton lint data from Baker (1987), Bauer and Busscher (1993), Busscher and Bauer (2003), Delaney et al. (2002), Denton and Tyler (2002), Endale et al. (2002), Hutchinson et al. (1993), Johnson et al. (2001), Lee et al. (2002), Mitchell et al. (2002), Nyakatawa and Reddy (2002), Nyakatawa et al. (2000), Parsch et al. (2001), Pettigrew and Jones (2001), Reeves and Delaney (2002), Schomberg et al. (2003), Triplett et al. (2002), and Wiatrak et al. (2002).

[e] Cotton seed data from Boquet and Coco (1993), Buntin et al. (2002), Burmester et al. (1993, 2002), Dabney et al. (1993), Gordon et al. (1990), Mutchler et al. (1985), Schwab et al. (2002), and Triplett et al. (1996).

[f] Peanut seed data from Cheshire et al. (1985), Johnson et al. (2001), Jordan et al. (2001, 2003), Marois and Wright (2003), and Wright and Teare (1993).

[g] Sorghum grain data from Bishnoi and Mays (2002), Franzluebbers et al. (1995a), Groffman et al. (1987), Langdale et al. (1984, 1990), Parsch et al. (2001), Richardson and King (1995), and Triplett et al. (2002).

[h] Soybean seed data from Bishnoi and Mays (2002), Edwards et al. (1988), Elmore and Heatherly (1988), Franzluebbers et al. (1995a), Hargrove et al. (1985), Hunt et al. (1985), Karlen et al. (1989), Langdale et al. (1990), Mitchell et al. (2002), NeSmith et al. (1987), Parsch et al. (2001), Popp et al. (2002), Raczkowski et al. (2002), Thurlow et al. (1985), Triplett et al. (2002), Wagger and Denton (1989, 1992), and Wesley et al. (1988).

[i] Wheat grain data from Franzluebbers et al. (1995a), Frederick and Bauer (1996), Karlen and Gooden (1987), Karlen et al. (1989), Langdale et al. (1984), Mitchell et al. (2002), Richardson and King (1995), Wagger and Denton (1989), and Wesley et al. (1988).

reported estimates of SOC sequestration with NT of 0.32 ± 0.15 Mg ha^{-1} $year^{-1}$ for western Canada ($n = 35$) and -0.07 ± 0.27 Mg ha^{-1} $year^{-1}$ for eastern Canada ($n = 63$). The lower rate of SOC sequestration in eastern compared with western Canada was attributed to higher native SOC levels, possibly less previous soil erosion, and greater decomposition of surface residues in the cool-humid climate of eastern Canada. Data analysis by Franzluebbers and Steiner (2002) suggested that climatic conditions may indeed play a prominent role in the potential for conservation tillage systems to sequester SOC. Tillage comparisons under moderate climatic conditions (i.e., 1.11–1.44 mm mean annual precipitation mm^{-1} mean annual potential evapotranspiration) had the highest SOC sequestration rate (0.50 Mg ha^{-1} $year^{-1}$) from a compilation of 111 comparisons from USA and Canada. This analysis of climatic conditions indicated that the southeastern USA was on the fringe of the maximum potential SOC sequestration. However, only seven of the 21 locations reported in the current analysis had been included previously. The current analysis suggests that the southeastern USA has equally high potential for SOC sequestration with adoption of NT compared with CT, as compared with the "optimum" zone in North America in the east-central USA. From a compilation of tillage studies around the world ($n = 93$), West and Post (2002) reported SOC sequestration with NT of 0.48 ± 0.13 Mg ha^{-1} $year^{-1}$ (mean of 15 years).

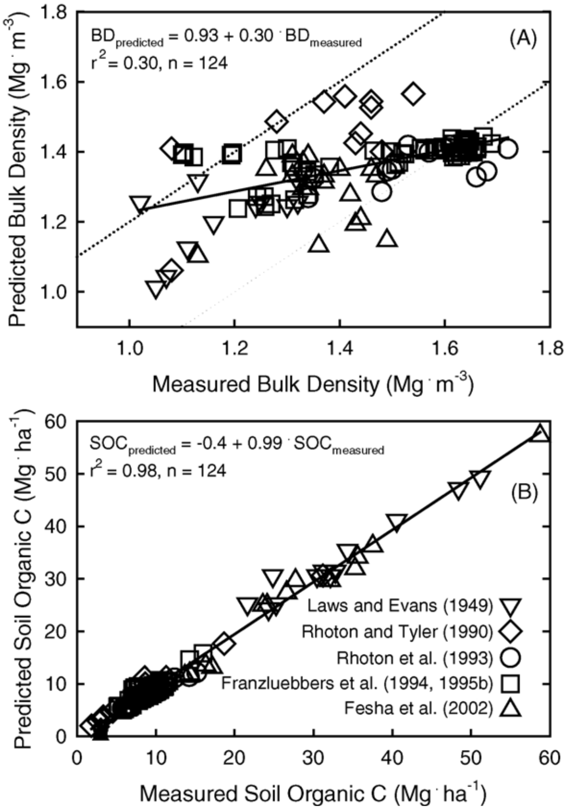

Fig. 11. Predicted and measured soil bulk density (A) and soil organic C (B) from six studies in Alabama, Mississippi, and eastern Texas. Bulk density was predicted from the non-linear equation: $BD = 0.3 + 1.28\ e^{-0.018SOC}$, where BD is bulk density ($Mg\ m^{-3}$) and SOC is soil organic C ($g\ kg^{-1}$) from 230 observations in a pasture experiment in Georgia at four depth intervals to 30 cm (Schnabel et al., 2001).

The ratio of SOC under NT-to-CT was $1.16 \pm 0.16\ kg\ kg^{-1}$ and significantly different from unity ($p < 0.001$). This value, calculated as ratios from individual tillage comparisons, suggests that an index of SOC content should be an average of 16% greater under NT than conventional inversion tillage in the southeastern USA. From a linear regression of SOC under NT on SOC under CT (Fig. 12A), the slope of 0.95 was not different ($p > 0.1$) from unity, but the intercept of 0.5 was greater ($p < 0.001$) than zero. These regression parameters suggested that ratios of SOC under NT-to-CT would be different, depending upon the initial C content of soil. When comparing the ratio of SOC under NT-to-CT with initial SOC, 33% of the variation in this ratio could be explained by the initial content of organic C present in soil under CT (Fig. 12B). This non-linear relationship suggests that soils initially low in SOC would show the greatest relative increases in SOC from management with reduced tillage. Soils initially low in SOC with CT might be very sandy soils with little protective capacity for organic matter or severely eroded soils.

When SOC with NT was regressed upon SOC with CT and the intercept forced through zero, the slope of 1.10 ± 0.01 was significantly greater ($p < 0.001$) than unity (Fig. 12A). This approach was used by VandenBygaart et al. (2003) as a means to evaluate the effect of SOC under NT compared with CT, resulting in slopes of 1.07 ± 0.02 in western Canada and 0.96 ± 0.04 in eastern Canada. The results presented here suggest that this approach would underestimate

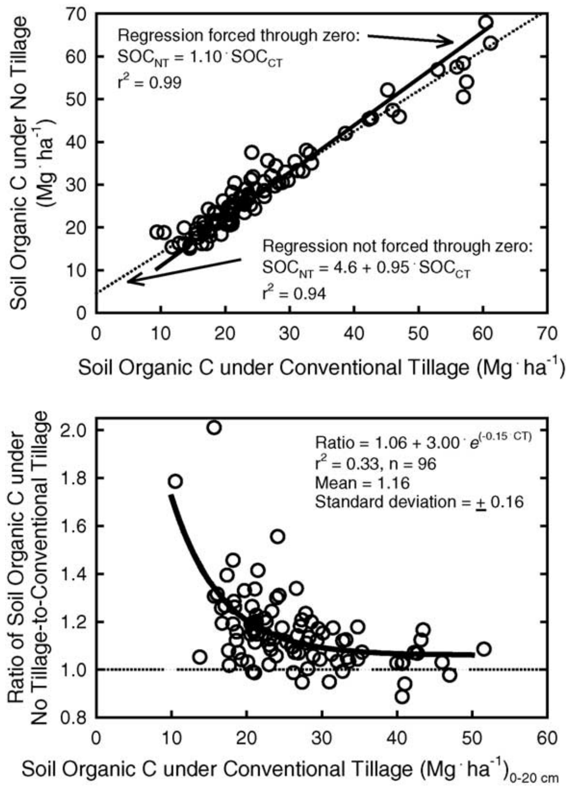

Fig. 12. Relationships between soil organic C under no tillage and conventional tillage (A) and the ratio of soil organic C under no tillage-to-conventional tillage and initial soil organic C under conventional tillage (B). The x-axis in Panel B is soil organic C adjusted to an equivalent depth of 20 cm for all observations. Data are from multiple references reported in Table 5.

Table 5
Soil organic C (SOC) and associated site characteristics from studies investigating tillage systems (CT is conventional tillage and NT is no tillage) in the southeastern USA

Location (city, state)	Soil taxonomy	Soil texture	Cropping system	Duration (years)	Depth (cm)	SOC ($Mg\ ha^{-1}$) CT	SOC ($Mg\ ha^{-1}$) NT	Reference
Auburn AL	Typic Paleudult	LS	SB	5	15	15.8	17.6	Rhoton et al. (1993)
Auburn AL	Typic Kanhapludult	FSL	CO (0N)	3.5	20	10.5	18.8	Siri-Prieto et al. (2002)
Auburn AL	Typic Kanhapludult	FSL	CO/CC (0N)	3.5	20	21.3	26.1	Siri-Prieto et al. (2002)
Auburn AL	Typic Kanhapludult	FSL	CO/CC - CN/CC (0N)	3.5	20	23.0	26.0	Siri-Prieto et al. (2002)
Auburn AL	Typic Kanhapludult	fSL	CO/CC - CN/CC (1N)	3.5	20	27.2	32.1	Siri-Prieto et al. (2002)
Auburn AL	Typic Kanhapludult	fSL	CO/CC - CN/CC - SB/WT (1N)	3.5	20	27.9	34.4	Siri-Prieto et al. (2002)
Bella Mina AL	Rhodic Paleudult	SiL	CO	12	24	22.4	27.2	Feng et al. (2002)
Brewton AL	Typic Paleudult	SL	SB/RY-CN/WT-CO/TR-GS/WL	17	30	30.8	35.4	Motta et al. (2002)
Crossville AL	Typic Hapludult	fSL	SB/WT	11	20	16.7	21.0	Edwards et al. (1992)
Crossville AL	Typic Hapludult	fSL	CN/WT	11	20	17.4	24.3	Edwards et al. (1992)
Crossville AL	Typic Hapludult	fSL	CN/WT - SB/WT	11	20	16.1	21.2	Edwards et al. (1992)
Crossville AL	Typic Hapludult		CN/WT	12	20	26.6	35.6	Fesha et al. (2002)
Crossville AL	Typic Hapludult		CN/WT - SB	12	20	24.1	37.5	Fesha et al. (2002)
Marvyn AL	Typic Kanhapludult	SL	CO/RY	25	20	18.3	23.5	Torbert et al. (2004)
Monroeville AL	Rhodic Paleudult	SCL	SB/RY-CN/WT-CO/TR-GS/WL	17	30	28.3	30.4	Motta et al. (2002)
Shorter AL	Typic Paleudult		CN/CC - SB/CC - CO/BO...	12	20	23.6	26.6	Fesha et al. (2002)
Shorter AL	Plinthic Paleudult	LS	CO - CN	4.5	30	20.7	21.7	Reeves and Delaney (2002)
Shorter AL	Typic Kandiudult	LS	CN/CC - SB/CC (no traffic)	7	20	17.7	18.0	Reicosky et al. (1999)
Shorter AL	Typic Kandiudult	LS	CN/CC - SB/CC (traffic)	7	20	16.8	20.0	Reicosky et al. (1999)
Athens GA	Rhodic Kanhapludult	SCL	GS/RY	13	15	26.1	30.7	Beare et al. (1994)
Athens GA	Rhodic Kanhapludult	SCL	GS/RY - SB/RY	5	21	27.7	29.7	Groffman (1984)
Athens GA	Rhodic Kanhapludult	SCL	GS/RY - SB/RY - CN/RY	16	21	22.3	26.9	Hendrix et al. (1998)
Athens GA	Rhodic Kanhapludult	SCL	GS/RY - SB/RY	13	21	23.6	27.1	Hu et al. (1995)
Athens GA	Rhodic Kanhapludult	SCL	GS	2	15	11.8	15.4	Hu et al. (1997)
Athens GA	Rhodic Kanhapludult	SCL	GS/RY - SB/RY	14	15	20.5	24.8	Hu et al. (1997)
Fort Valley GA	Typic Kandiudult	SL	TO - CN (0N)	5	20	20.1	20.8	Sainju et al. (2002a)
Fort Valley GA	Typic Kandiudult	SL	TO - CN (1N)	5	20	20.8	20.6	Sainju et al. (2002a)
Fort Valley GA	Typic Kandiudult	SL	TO - CN (2N)	5	20	21.0	20.8	Sainju et al. (2002a)
Fort Valley GA	Typic Kandiudult	SL	TO/HV - CN/HV (0N)	5	20	21.0	24.3	Sainju et al. (2002a)
Fort Valley GA	Typic Kandiudult	SL	TO/HV - CN/HV (1N)	5	20	21.1	24.7	Sainju et al. (2002a)
Fort Valley GA	Typic Kandiudult	SL	TO/HV - CN/HV (2N)	5	20	20.8	24.3	Sainju et al. (2002a)
Griffin GA	Typic Kanhapludult	SL	SB-RY - GS/CC - SB/WT	16	30	45.2	52.1	Hendrix et al. (1998)
Griffin GA	Typic Kanhapludult	SL	GS/CC	2	15	20.5	24.8	Hu et al. (1997)
Watkinsville GA	Typic Kanhapludult	SL	GS/RY-SB/CC-CO/BL-GS/WT	25	12	9.4	18.9	Franzluebbers (2002)
Watkinsville GA	Typic Kanhapludult	SL	ML/CC - CO/RY	4	15	21.1	21.2	Franzluebbers et al. (1999a)
Watkinsville GA	Typic Kanhapludult	SL	ML/CC - CO/RY (w/residue)	4	15	21.2	24.1	Franzluebbers et al. (1999a)
Watkinsville GA	Typic Hapludult	SL	GS	15	15	26.1	27.2	Rhoton et al. (1993)
Accokeek MD	Aquic Hapludult	SL	SB/WT - CN	6	15	14.5	15.1	Weil et al. (1993)
Clarksville MD	Aquic Hapludult	SiL	CN (0N)	18	20	31.3	33.3	McCarty and Meisinger (1997)
Clarksville MD	Aquic Hapludult	SiL	CN (1N)	18	20	33.4	35.0	McCarty and Meisinger (1997)
Clarksville MD	Aquic Hapludult	SiL	CN (2N)	18	20	33.2	37.3	McCarty and Meisinger (1997)
Clarksville MD	Typic Hapludult	SiL	CN	11	28	60.5	67.9	Weil et al. (1988)
Queenstown MD	Aquic Hapludult	SiL	CN (0N)	21	20	26.1	28.6	McCarty and Meisinger (1997)
Queenstown MD	Aquic Hapludult	SiL	CN (1N)	21	20	32.1	33.1	McCarty and Meisinger (1997)
Queenstown MD	Aquic Hapludult	SiL	CN (2N)	21	20	29.4	32.9	McCarty and Meisinger (1997)
Queenstown MD	Aquic Hapludult	SiL	CN	3	20	21.4	24.5	McCarty et al. (1998)
Queenstown MD	Aquic Hapludult	SiL	CN	11	28	57.0	50.5	Weil et al. (1988)
Salisbury MD	Typic Hapludult	SiL	CN (−P)	11	28	56.9	58.4	Weil et al. (1988)
Salisbury MD	Typic Hapludult	SiL	CN (+P)	11	28	56.0	57.5	Weil et al. (1988)
Salisbury MD	Typic Hapludult	SiL	CN (+2P)	11	28	57.5	54.0	Weil et al. (1988)
Senatobia MS	Glossic Fragiudalf	SiL	CO/WT	9	15	13.6	16.2	Rhoton et al. (2002)
Senatobia MS	Glossic Fragiudalf	SiL	CN/HV	9	15	13.6	19.9	Rhoton et al. (2002)
Senatobia MS	Glossic Fragiudalf	SiL	CO/WT	8	15	15.4	18.4	Rhoton (2002)
Senatobia MS	Glossic Fragiudalf	SiL	CN/HV	8	15	15.6	18.7	Rhoton (2002)
Senatobia MS	Glossic Fragiudalf	SiL	SB/WT	8	15	15.5	19.6	Rhoton (2002)
Verona MS	Fluvaquentic Hapludoll	SiCL	SB	5	15	24.6	24.4	Rhoton et al. (1993)
Goldsboro NC	Aquic Hapludult	L	CN - SB/WT	6	12.5	19.4	18.4	Naderman et al. (2004)
Goldsboro NC	Aquic Hapludult	L	CN - SB	6	12.5	17.1	16.2	Naderman et al. (2004)
Goldsboro NC	Aquic Hapludult	L	CN - SB/WT	6	12.5	17.5	19.4	Naderman et al. (2004)
Goldsboro NC	Aquic Hapludult	L	CN - PN - CO	6	12.5	16.4	16.2	Naderman et al. (2004)
Goldsboro NC	Typic Hapludult	SL	CN - SB	6	12.5	17.9	21.4	Naderman et al. (2004)
Goldsboro NC	Typic Hapludult	SiL	CN - SB/WT	6	12.5	20.5	23.0	Naderman et al. (2004)
Goldsboro NC	Typic Hapludult	SiL	CN - PN - CO	6	12.5	21.0	21.7	Naderman et al. (2004)
Goldsboro NC	Typic Hapludult	SL	CN - SB	6	12.5	16.7	19.1	Naderman et al. (2004)

Table 5 (*Continued*)

Location (city, state)	Soil taxonomy	Soil texture	Cropping system	Duration (years)	Depth (cm)	SOC ($Mg ha^{-1}$) CT	SOC ($Mg ha^{-1}$) NT	Reference
Goldsboro NC	Typic Hapludult	SL	CN - PN - CO	6	12.5	14.5	15.8	Naderman et al. (2004)
Goldsboro NC	Aquic Hapludult	L	CN - SB	6	12.5	18.4	21.6	Naderman et al. (2004)
Florence SC	Typic Kandiudult	LS	CN - SB/WT - CO/WT	19	15	32.6	38.0	Ding et al. (2002)
Florence SC	Typic Kandiudult	LS	CN - SB/WT - CO/WT	11.5	15	12.9	16.3	Hunt et al. (1996)
Florence SC	Typic Kandiudult	LS	CN - SB/WT - CO/WT	8	15	23.6	27.7	Karlen et al. (1989)
Florence SC	Typic Kandiudult	LS	CN - SB/WT - CO/WT (1 depth)	18	15	20.2	21.6	Novak et al. (1996)
Florence SC	Typic Kandiudult	LS	CN - SB/WT - CO/WT (by layers)	18	15	19.0	21.2	Novak et al. (1996)
College Station TX	Fluventic Ustochrept	SiCL	WT (0N)	9	20	23.9	25.3	Franzluebbers et al. (1994)
College Station TX	Fluventic Ustochrept	SiCL	WT (2N)	9	20	24.7	29.0	Franzluebbers et al. (1994)
College Station TX	Fluventic Ustochrept	SiCL	SB/WT - GS (0N)	9	20	23.3	29.0	Franzluebbers et al. (1994)
College Station TX	Fluventic Ustochrept	SiCL	SB/WT - GS (2N)	9	20	24.3	31.8	Franzluebbers et al. (1994)
College Station TX	Fluventic Ustochrept	SiCL	SB/WT (0N)	9	20	21.5	30.4	Franzluebbers et al. (1994)
College Station TX	Fluventic Ustochrept	SiCL	SB/WT (2N)	9	20	21.5	30.4	Franzluebbers et al. (1994)
College Station TX	Fluventic Ustochrept	SiCL	GS (0N)	9.5	20	23.0	23.5	Franzluebbers et al. (1995b)
College Station TX	Fluventic Ustochrept	SiCL	GS (2N)	9.5	20	23.0	25.4	Franzluebbers et al. (1995b)
College Station TX	Fluventic Ustochrept	SiCL	GS - SB/WT (0N)	9.5	20	28.9	30.5	Franzluebbers et al. (1995b)
College Station TX	Fluventic Ustochrept	SiCL	GS - SB/WT (2N)	9.5	20	29.8	31.0	Franzluebbers et al. (1995b)
College Station TX	Fluventic Ustochrept	SiCL	SB	10	20	19.7	26.2	Franzluebbers et al. (1998)
College Station TX	Fluventic Ustochrept	SiCL	GS (3N)	10	20	21.1	28.2	Franzluebbers et al. (1998)
College Station TX	Fluventic Ustochrept	SiCL	WT (3N)	10	20	22.6	27.1	Franzluebbers et al. (1998)
College Station TX	Fluventic Ustochrept	SiCL	SB/WT - GS (1N)	10	20	26.0	28.5	Franzluebbers et al. (1998)
College Station TX	Fluventic Ustochrept	SiCL	SB/WT (1N)	10	20	24.0	31.2	Franzluebbers et al. (1998)
Corpus Christi TX	Typic Ochraqualf	SCL	CO - CN (1N)	15	20	17.6	19.0	Potter et al. (1998)
Corpus Christi TX	Typic Ochraqualf	SCL	CO - CN (5N)	15	20	18.6	20.9	Potter et al. (1998)
Corpus Christi TX	Typic Ochraqualf	SCL	CN - CO (5N)	15	20	18.4	23.2	Potter et al. (1998)
Corpus Christi TX	Typic Ochraqualf	SCL	CN - CO	15	20	18.7	21.6	Salinas-Garcia et al. (1997)
Temple TX	Udic Pellustert	C	WT - CN -GS -CO	10	30	53.0	56.9	Potter and Chichester (1993)
Temple TX	Udic Pellustert	C	GS - CN - WT (1N)	10	20	46.0	47.4	Potter et al. (1998)
Temple TX	Udic Pellustert	C	GS - CN - WT (5N)	10	20	47.0	45.9	Potter et al. (1998)
Temple TX	Udic Pellustert	C	WT - GS - CN (1N)	10	20	42.3	45.3	Potter et al. (1998)
Temple TX	Udic Pellustert	C	WT - GS - CN (5N)	10	20	42.7	45.6	Potter et al. (1998)
Temple TX	Udic Pellustert	C	GS	3	30	61.2	63.1	Reicosky et al. (1997)
Mean ± S.D.				10 ± 5	19 ± 5	25.2 ± 11.6	28.5 ± 11.3	

Cropping systems were defined as: BL, barley; CC, crimson clover; CN, corn; CO, cotton; GS, grain sorghum; HV, hairy vetch; ML, millet; PN, peanut; RY, rye; SB, soybean; TO, tomato; TR, triticale; WL, white lupin; WT, wheat. '-' separates years and '/' separates crops within a year. Values in parentheses are relative N fertilizer rates.

the potential of NT to sequester SOC, because soils with very low organic C can respond more favorably to conservation management than soils with high organic C.

3.2.3. Interaction of tillage with cover cropping

When tillage studies were sorted to those without ($n = 40$) and with ($n = 53$) cover cropping, the effect of a ''conservation tillage system'' on SOC sequestration became more apparent (Table 6). The benefits of conservation tillage on soil quality may be dependent upon sufficient crop residue at the soil surface (Reeves, 1997; Truman et al., 2003). Soil organic C sequestration with NT was about two times greater with cover cropping than without cover cropping (0.53 and 0.28 $Mg ha^{-1} year^{-1}$, respectively, $p < 0.01$). The ratio of SOC with NT-to-CT averaged 1.20 with cover cropping and 1.11 without cover cropping. No tillage with cover cropping in the warm-humid region of the southeastern USA most likely adds C to the soil through above- and below-ground cover crop production, but also possibly by limiting decomposition of organic matter in soil that is dried during cover crop growth. By shifting predominant utilization of soil water from heterotrophic to autotrophic organisms, greater SOC sequestration may be possible.

Greater SOC without than with cover cropping under both conventional and NT (Table 6) should not be interpreted to indicate that cover cropping reduced SOC stock. Rather, this difference was probably a function of the following factors in this unpaired analysis: (1) greater soil depth without cover cropping and (2) more studies without cover cropping in Texas and Maryland, which are at the edges of the southeastern USA region where inherent SOC values were typically higher than the rest of the region.

3.2.4. Interaction of tillage with crop complexity

From those studies with comparison of conventional and NT, there were 15 comparisons that allowed

Table 6
Soil organic C under conventional tillage and no tillage sorted by cropping systems without and with cover crops

Property	Without cover crop (n = 40)		t-Test, Pr > F	With cover crop (n = 53)	
	Mean	S.D.		Mean	S.D.
Soil depth (cm)	21	4	0.007	18	5
Duration of comparison (years)	12	5	0.006	9	5
Soil organic C with conventional tillage (Mg ha^{-1})	30.9	14.9	<0.001	21.5	6.3
Soil organic C with no tillage (Mg ha^{-1})	33.4	14.3	<0.001	25.4	7.3
Difference in soil organic C between tillage systems (Mg ha^{-1})	2.5	2.8	0.01	3.9	2.8
Yearly difference in soil organic C between tillage systems (Mg ha^{-1} $year^{-1}$)	0.28	0.44	0.009	0.53	0.45
Ratio of soil organic with no tillage-to-conventional tillage (kg kg^{-1})	1.11	0.15	0.02	1.20	0.17

Data are from multiple references reported in Table 5.

calculation of SOC sequestration due to more complex crop rotation. Simpler rotations had 1.7 ± 0.8 crops per rotation cycle and more complex rotations had 2.9 ± 0.7 crops per rotation cycle. Total and yearly SOC sequestration with more complex compared with simpler crop rotation were significantly greater ($p < 0.001$) than zero, averaging 1.79 Mg ha^{-1} and 0.22 Mg ha^{-1} $year^{-1}$, respectively. VandenBygaart et al. (2003) reported SOC sequestration with increases in rotation complexity (mainly by eliminating fallow) in Canada of 0.17 ± 0.18 Mg ha^{-1} $year^{-1}$. From a global dataset, West and Post (2002) reported SOC sequestration with enhancing crop rotation (defined as change from monoculture to crop rotation, crop-fallow to continuous cropping, and increasing the number of crops in rotation) of 0.15 ± 0.11 Mg ha^{-1} $year^{-1}$.

The number of observations in our analysis was relatively few and variability among studies was high resulting in no significant interaction between tillage system and crop rotation on SOC sequestration. Soil organic C sequestration due to crop rotation complexity was statistically similar under NT (0.27 ± 0.32 Mg ha^{-1} $year^{-1}$) as under CT (0.16 ± 0.35 Mg ha^{-1} $year^{-1}$) ($p = 0.28$). The simple and complex crop rotations in this analysis were towards the upper end of cropping intensity (i.e., 0.76 ± 0.26 and 0.88 ± 0.13, respectively, expressed as fraction of year in cropping). With a wider range in cropping intensity, SOC sequestration with NT compared with CT increased with increasing cropping intensity using data compiled from USA and Canada (Franzluebbers and Steiner, 2002).

3.2.5. *Interaction of tillage with N fertilization*

From those studies with comparison of conventional and NT, there were 13 comparisons that allowed calculation of SOC sequestration due to N fertilization. There was no significant interaction between tillage system and N fertilization on SOC sequestration ($p = 0.27$ for linear component and $p = 0.71$ for quadratic component) (Fig. 13). Across tillage systems, SOC sequestration was optimized (0.28 Mg ha^{-1} $year^{-1}$) with 171 kg N ha^{-1} $year^{-1}$. Assuming a C cost of 1.23 kg C kg^{-1} N fertilizer for manufacturing, distributing, and applying commercial N fertilizer (Izaurralde et al., 1998), maximum net C offset would be achieved with 107 kg N ha^{-1} $year^{-1}$ to obtain SOC sequestration of 0.24 Mg ha^{-1} $year^{-1}$. Assuming a lower C cost of 0.98 kg C kg^{-1} N fertilizer (0.86 + 0.08 + 0.04 for production, application, and liming components, respectively; West and Marland, 2002), maximum C offset would be achieved with 120 kg N ha^{-1} $year^{-1}$ to obtain SOC sequestration of 0.26 Mg ha^{-1} $year^{-1}$. These calculations do not include the global warming potential of nitrous oxide emission that accompanies N fertilizer application (IPCC, 1997). Using a global warming potential for nitrous oxide 296 times that of carbon dioxide and a nitrous oxide emission factor of 1.25% of applied N (IPCC, 1997), an additional C cost of 1.586 kg C kg^{-1} N fertilizer due to nitrous oxide emission would be applicable. Optimum fertilization to maximize net C offset would then be 24 to 37 kg N ha^{-1} $year^{-1}$ to achieve SOC sequestration of 0.07 to 0.11 Mg ha^{-1} $year^{-1}$. The additional C stored with different fertilization optima from 24 to 120 kg

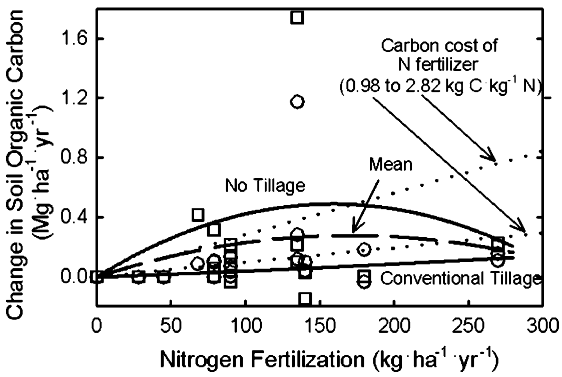

Fig. 13. Response of soil organic C to N fertilization. Values at lowest N fertilizer variable within a study were set to zero. Data from Franzluebbers et al. (1994, 1995b), McCarty and Meisinger (1997), Potter et al. (1998), Sainju et al. (2002a) and Siri-Prieto et al. (2002).

N ha^{-1} year^{-1} would be 2.13 to 3.05 kg C kg^{-1} fertilizer-N applied, respectively. These SOC conversion efficiencies of N fertilizer surround the value of 2.5 kg kg^{-1} fertilizer-N applied reported by Franzluebbers and Steiner (2002) for 15 comparisons of tillage systems in the USA and Canada. A value of 1.5 to 4.1 kg SOC sequestered kg^{-1} fertilizer-N applied was reported for an analysis of several long-term studies in Canada, depending upon the range of fertilization (VandenBygaart et al., 2003). Although tillage systems did not respond to N fertilization significantly different, a calculation of N fertilization to achieve optimum SOC sequestration for NT was 159 kg N ha^{-1} year^{-1} and to achieve maximum net C offset was 87 to 134 kg N ha^{-1} year^{-1} (levels that produced SOC sequestration of 0.39–0.48 Mg ha^{-1} year^{-1} for C conversion efficiencies of 3.59–4.50 kg kg^{-1} fertilizer-N applied).

3.2.6. Research evaluation and needs to characterize the effects of tillage on soil C sequestration

A fairly extensive database has been assembled on the effects of NT in comparison with conventional inversion tillage on SOC. However, there are many forms of conservation tillage that are practically implemented in different areas of the southeastern USA. Further work is needed to describe how SOC is affected by variations in the extent of planting disturbances, periodic non-inversion tillage to eliminate weed or soil physical constraints, types of cover crops, crop rotations, etc. Quantitative relationships are also needed to describe the residue returned to the soil surface and potential gain in SOC in the long term. Although 78% of the comparisons of NT with CT in this review were for >5 years, only 5% were >20 years. More long-term investigations are needed to adequately describe SOC under steady-state cropping conditions. In addition, detailed sampling of conservation tillage systems with time is needed to more accurately determine whether SOC is actually increasing with time or simply being lost at a slower rate than under CT. There is a need to expand the work of conservation tillage systems research into investigations of SOC on a diversity of farms to assess various landscape variables, as well as management variables to include greater crop diversity, rotations of annual crops with perennial crops, biomass fuel harvest, animal manures applied as fertilizer, periodic animal grazing of cover crops, etc.

3.3. Fertilization and manure application

Nutrients supplied via commercial fertilizers, animal manures, and organic by-products would be expected to increase SOC by increasing C input from enhanced plant productivity and crop residue returned to soil. There are relatively few studies available to assess long-term fertilization effects on SOC in the southeastern USA, other than those already mentioned previously in the section on tillage. On an Udertic Paleustoll in central Oklahoma, winter wheat was grown continuously for 24 years with four different N fertilizer rates (Raun et al., 1998). Only at the highest N rate (134 kg N ha^{-1} year^{-1}) was there a change in SOC at a depth of 0–30 cm, resulting in a sequestration estimate of 0.05 Mg ha^{-1} year^{-1}. In this same study at a depth of 0–15 cm, SOC conversion efficiency with application of 90 kg N ha^{-1} year^{-1} was calculated as 2.1 kg C kg^{-1} fertilizer-N applied (Westerman et al., 1994), similar to the average value of 2.5 kg C kg^{-1} fertilizer-N applied from the analysis of tillage studies reported in the previous section. On a Typic Hapludult in Alabama, fertilization of continuous cotton (no cover crop) with 134 kg N ha^{-1} year^{-1} compared with no fertilizer for 35 years resulted in sequestration of SOC at a mean rate of 0.32 Mg ha^{-1} year^{-1} (Mitchell and Entry, 1998).

Under the same conditions in a corn-cotton rotation with legume cover crop, SOC sequestration was 0.11 Mg ha^{-1} year^{-1}. SOC conversion efficiency of applied N was calculated as 0.8 kg C kg^{-1} fertilizer-N applied in the cotton-corn rotation with cover crop and 2.4 kg C kg^{-1} fertilizer-N applied in continuous cotton without cover crop. It seems likely that biological N fixation from the legume cover crop reduced the need for additional fertilizer, and hence, reduced the SOC conversion efficiency of applied N, especially since SOC was higher in the rotation with cover crop and without N fertilizer (9.5 g kg^{-1}) than in the system without cover crop and with N fertilizer (8.4 g kg^{-1}).

Data to assess the effect of inorganic fertilizers, other than N, on organic C of soils in the southeastern USA are scant. Application of 20 and 78 kg P ha^{-1} year^{-1} to corn for 11 years resulted in a decline of SOC of 0.13 ± 0.19 Mg ha^{-1} year^{-1} (Weil et al., 1988). The reason for this decline is not apparent.

Poultry production in the southeastern USA is widespread (Fig. 6). Utilization of litter from confinement houses as fertilizer on crop and pasture land is common, because it provides a good source of many nutrients and is generally less expensive than inorganic fertilizer. Frequent and heavy application of poultry litter to land in the immediate vicinity of houses has occurred in the past to reduce the cost of transportation. This practice can lead to high nutrient levels in surface soils, especially N and P, which can run off of fields into nearby surface waters and reduce water quality (Moore et al., 1995).

Application of poultry litter to crop and pasture land has been investigated in a number of studies, although typically in 2-year studies, which limits the sensitivity of SOC sequestration values (Table 7). From a total of 19 comparisons, SOC with manure application was 11% greater than without ($p = 0.09$). By limiting comparisons to only those conducted >2 years, SOC with manure application (36.7 Mg ha^{-1}) was greater ($p = 0.05$) than without manure application (30.6 Mg ha^{-1}). Soil organic C sequestration with the application of poultry litter compared with unmanured soil was 0.26 ± 2.15 Mg ha^{-1} year^{-1} among all 19 comparisons. Limiting comparisons to only those conducted for >2 years, SOC sequestration with poultry litter was 0.72 ± 0.67 Mg ha^{-1} year^{-1}. The conversion of C contained in poultry litter to SOC was 17 ± 15%. The rate of SOC accumulation from land application of animal manure in other parts of the world include 0.10–0.23 Mg ha^{-1} year^{-1} during 18 years in Kenya (Kapkiyai et al., 1999), 0.15 Mg ha^{-1} year^{-1} during 60 years in Denmark (Christensen, 1988), 0.20 Mg ha^{-1} year^{-1} during 22 years in Italy (Govi et al., 1992), 0.20–0.22 Mg ha^{-1} year^{-1} during 45 years in Nigeria (Agbenin and Goladi, 1997), 0.21–0.54 Mg ha^{-1} year^{-1} during 20 years in India (Gupta et al., 1992), 0.50 Mg ha^{-1} year^{-1} during 135 years in England (Webster and Goulding, 1989), and 1.02 Mg ha^{-1} year^{-1} during 4 years in England (Bhogal and Shepherd, 1997). Soil organic C accumulation rates with poultry litter application in the southeastern USA are in the upper part of the range reported for other studies around the world, but this divergence may have been due differences in the source of animal manure (typically cattle manure in other parts of the world) and the length of time of investigations.

3.3.1. Research evaluation and needs to characterize the effects of fertilization and manure application on soil C sequestration

A less-than-adequate number of datasets is currently available to characterize fertilization and manure application effects on SOC in the southeastern USA. The long-term 'Old Rotation' plots in Alabama and long-term wheat plots in Oklahoma are examples of valuable resources to investigate the effects of fertilizer and manure management on SOC sequestration and greenhouse gas emissions. The high variability of SOC sequestration exhibited with several of the 2-year manure experiments suggests that longer-term studies should be encouraged to improve these estimates. In addition, with random variation in soil properties often limiting detection of small differences, repeated sampling of soil with time would improve estimates of SOC sequestration. Further work is needed to quantify the effects of moderate application of animal manure to crops and pastures to avoid the increased potential for denitrification and nutrient (N and P) pollution associated with heavy manure application at disposal rates. Small to moderate application rates would allow producers to potentially build soil organic matter and utilize nutrients most efficiently, assuming supplemental needs for inorganic fertilization could be accurately assessed.

Table 7
Soil organic C and associated site characteristics from studies investigating animal manure application to land in the southeastern USA

Location	Soil taxonomy	Experimental conditions	Duration (years)	Soil organic C ($Mg\ ha^{-1}$)			Reference
				Without manure	Low manure rate	High manure rate	
Bella Mina AL	Rhodic Paleudult	Corn, 9 and 18 $Mg\ ha^{-1}\ year^{-1}$ litter applied, 0–30 cm, 2% slope	2	23.4	24.2	24.8	Wood et al. (1996)
Bella Mina AL	Rhodic Paleudult	Corn, 9 and 18 $Mg\ ha^{-1}\ year^{-1}$ litter applied, 0–30 cm, 4% slope	2	30.1	20.1	23.7	Wood et al. (1996)
Bella Mina AL	Rhodic Paleudult	Cotton/rye, 6 and 12.7 $Mg\ ha^{-1}\ year^{-1}$ litter applied, 0–15 cm	2	21.3	26.2	32.3	Nyakatawa et al. (2001)
Headland AL	Plinthic Paleudult	Corn, 9 $Mg\ ha^{-1}\ year^{-1}$ litter applied, 0–10 cm, conventional tillage	2	8.4	9.4		Kingery et al. (1996)
Headland AL	Plinthic Paleudult	Corn, 9 $Mg\ ha^{-1}\ year^{-1}$ litter applied, 0–10 cm, strip tillage	2	9.5	9.0		Kingery et al. (1996)
Northern AL	Hapludults, Fragiudults	12 sites, tall fescue grazed/hayed, 10.9 ± 5.4 $Mg\ ha^{-1}\ year^{-1}$ litter applied, 0–30 cm	21 ± 4	31.4	37.2		Kingery et al. (1994)
Farmington GA	Typic Kanhapludult	Bermudagrass, 5.4 $Mg\ ha^{-1}\ year^{-1}$ litter applied, 0–20 cm, unharvested	5	37.2	42.6		Franzluebbers et al. (2001)
Farmington GA	Typic Kanhapludult	Bermudagrass, 5.4 $Mg\ ha^{-1}\ year^{-1}$ litter applied, 0–20 cm, low grazing pressure	5	43.5	41.5		Franzluebbers et al. (2001)
Farmington GA	Typic Kanhapludult	Bermudagrass, 5.4 $Mg\ ha^{-1}\ year^{-1}$ litter applied, 0–20 cm, high grazing pressure	5	40.8	42.5		Franzluebbers et al. (2001)
Farmington GA	Typic Kanhapludult	Bermudagrass, 5.4 $Mg\ ha^{-1}\ year^{-1}$ litter applied, 0–20 cm, hayed	5	36.3	39.1		Franzluebbers et al. (2001)
Watkinsville GA	Typic Kanhapludult	Tall fescue hay, 45 and 269 $Mg\ ha^{-1}\ year^{-1}$ litter applied, 0–30 cm	2	26.1	23.0	23.8	Jackson et al. (1977)
Eastern OK	Hapludults, Paleudults, Hapludalfs, Paleudalfs, Fragiudalfs	12 sites, bermudagrass hay, 6.7 ± 1.8 $Mg\ ha^{-1}\ year^{-1}$ litter applied, 0–5 cm	19 ± 10	14.3	20.0		Sharpley et al. (1993)
Eastern OK	Hapludults, Paleudults, Hapludalfs, Paleudalfs, Fragiudalfs	12 sites, bermudagrass hay, 6.7 ± 1.8 $Mg\ ha^{-1}\ year^{-1}$ litter applied, 0–30 cm depth assuming $C = 10 \times$ total N	19 ± 10	27.8	49.9		Sharpley et al. (1993)
Orange VA	Rhodic Paleudult	Corn, 0, 54, and 110 $Mg\ ha^{-1}\ year^{-1}$ layer manure, 0–8 cm, conventional tillage	5	13.6	20.8	21.9	Weil and Kroontje (1979)
Mean ± S.D.			7 ± 7	26.0 ± 11.5	29.0 ± 13.0	25.3 ± 4.1	

3.4. Forage management and grazing

Available literature quantifying the effects of forage management and animal grazing on SOC is limited in the southeastern USA, despite the extent of forages grown in the region (Fig. 4). From 12 comparisons, the rate of SOC sequestration following establishment of various forages ranged from 0.22 to 2.90 $Mg\ ha^{-1}\ year^{-1}$, averaging 1.03 ± 0.90 $Mg\ ha^{-1}\ year^{-1}$ (Table 8). The average rate of SOC sequestration with grass establishment was 2.6 times greater than the average rate of SOC sequestration with no-tillage crop production. This difference in sequestration potential was directly compared in an

Table 8
Rate of soil organic C sequestration following grass establishment in the southeastern USA

Location	Soil taxonomy	Experimental conditions	Duration (years)	Soil organic C sequestration (Mg ha^{-1} year^{-1})	Reference
Tallassee AL	Typic Hapludult	'Alamo', 'Kanlow', and 'Cave-in-Rock' switchgrass in 15-cm rows, 30-cm depth	10	0.48	Ma et al. (2000)
Farmington GA	Typic Kanhapludult	Unharvested 'Coastal' bermudagrass with inorganic, clover cover crop, and broiler litter fertilization, 6-cm depth	5	0.65	Franzluebbers et al. (2001)
Farmington GA	Typic Kanhapludult	Grazed 'Coastal' bermudagrass at low pressure with inorganic, clover cover crop, and broiler litter fertilization, 6-cm depth	5	1.41	Franzluebbers et al. (2001)
Farmington GA	Typic Kanhapludult	Grazed 'Coastal' bermudagrass at high pressure with inorganic, clover cover crop, and broiler litter fertilization, 6-cm depth	5	1.40	Franzluebbers et al. (2001)
Farmington GA	Typic Kanhapludult	Hayed 'Coastal' bermudagrass with inorganic, clover cover crop, and broiler litter fertilization, 6-cm depth	5	0.29	Franzluebbers et al. (2001)
Watkinsville GA	Typic Kanhapludult	Unharvested tall fescue established every year until sampling, 30-cm depth	5	2.59	Giddens et al. (1971)
Watkinsville GA	Typic Kanhapludult	Grazed 'Kentucky-31' tall fescue chronosequence of 10, 17, and 50 years, 20-cm depth	10 30	1.00 0.65	Franzluebbers et al. (2000b)
Watkinsville GA	Typic Kanhapludult	Hayed 'Coastal' bermudagrass chronosequence of 6, 15, and 40 years, 20-cm depth	10 30	0.33 0.22	Franzluebbers et al. (2000b)
Temple TX	Oxyaquic Hapludert	Warm-season, tallgrass chronosequence of 6, 26, and 60 years, 60-cm depth	60	0.45	Potter et al. (1999)
Five locations in TX	Fluventic Ustochrept, Udic Pellustert, Udic Paleustalf	1- and 2-cut 'Alamo' and 'Caddo' switchgrass, 30-cm depth	5	2.90	Sanderson et al. (1999)
Mean ± S.D.			15 ± 17	1.03 ± 0.90	

adjacent long-term land use comparison, where SOC under 20-year-old tall fescue-bermudagrass pasture was 7.6 Mg ha^{-1} greater than under 24-year-old no-tillage cropland (Franzluebbers et al., 2000b).

The effect of animal grazing on SOC has only been investigated in a few studies in the southeastern USA. At a coastal marshland in North Carolina on a Typic Psammaquent, the effect of grazing by feral ponies reduced above-ground biomass by 23–40% and reduced SOC from 68.4 Mg ha^{-1} without grazing to 20.2 Mg ha^{-1} with grazing (Reader and Craft, 1999). Although the duration of feral pony grazing was not reported and the grazing variable unreplicated, trampling significantly increased soil bulk density. The sensitive condition of soil in coastal wetlands contrasts strongly with results obtained from upland soils. Soil organic C (0- to 30-cm depth) at the end of 10 years of management in Oklahoma was 56.1 ± 5.3 Mg ha^{-1} with cattle grazing and 70.8 Mg ha^{-1} in ungrazed exclosures on a fine-textured Udertic Argiustoll and was 35.5 ± 2.5 Mg ha^{-1} with cattle grazing and 26.3 Mg ha^{-1} in ungrazed exclosures on a coarse-textured Udic Argiustoll (Potter et al., 2001). From a survey of three pairs of grazed and hayed bermudagrass fields managed for 15–19 years, SOC was 6.9 Mg ha^{-1} greater (22%) with grazing than without grazing (Franzluebbers et al., 2000b). Return of feces to the land where forage was produced without significant soil compaction on these firmer upland soils was the most likely reason for this different response in SOC to grazing. From another experiment in the Piedmont of Georgia, SOC at the end of 5 years of management was not different between unharvested and hayed bermudagrass to a depth of 20 cm (38.1 ± 2.5 Mg ha^{-1}), but SOC was greater under cattle grazing systems (42.1 ± 1.4 Mg ha^{-1}) (Franzluebbers et al., 2001). The mean rate of additional organic C stored in soil due to grazing compared with haying in these two studies in Georgia was 0.76 ± 0.60 Mg ha^{-1} year^{-1}, which was 1.8 times higher than the mean rate of SOC sequestration with no-tillage compared with conventional-tillage cropping in the southeastern USA.

Other management variables that could affect SOC in pastures are plant species, fertilization, residue management, and animal behavior. On a Coastal Plain soil in Georgia, forage management effects on SOC were not significant for (1) with and without crimson clover planted into bermudagrass harvested for hay, (2) fertilization (0, 70, and 140 kg N ha^{-1} year^{-1}) of bermudagrass for hay during 6 years, and (3) burning bahiagrass annually, biennially, or not for 4 years (DeVane et al., 1952). An increase in SOC with broiler litter fertilization compared with inorganic fertilization of pastures was 0.27 ± 0.76 Mg ha^{-1} year^{-1} from studies in Alabama, Georgia, and Oklahoma (Table 7). At the end of 15 years of tall fescue fertilization in Georgia, SOC to a depth of 30 cm was 47.6 Mg ha^{-1} under high fertilization and 45.0 Mg ha^{-1} under low fertilization (Schnabel et al., 2001), a difference of 2.6 Mg ha^{-1} or 0.17 Mg ha^{-1} year^{-1}. The C cost (0.98–2.82 kg C kg^{-1} fertilizer N) of the 202 kg N ha^{-1} year^{-1} greater fertilization rate would have been 3.0–8.5 Mg ha^{-1}, indicating that the higher fertilizer rate would not have been beneficial for C conservation in the long term. Ma et al. (2000) found no difference in SOC due to N fertilization rate, row spacing, and cultivar at the end of 3 years of switchgrass growth.

Endophyte infection of tall fescue was found to increase SOC in pastures that were 8 and 15 years old (Franzluebbers et al., 1999b). To a depth of 15 cm, SOC was 2.1 Mg ha^{-1} greater with high than low endophyte infection. Wild-type endophyte infection of tall fescue can greatly reduce animal performance and productivity, as well as grazing behavior (Stuedemann and Hoveland, 1988). Both greater productivity of endophyte-infected tall fescue and reduced soil microbial activity were likely causes for this increase in SOC. Behavior of cattle on pastures has also been shown to affect distribution of feces and subsequent accumulation of SOC. With more time spent near shade and water sources, deposition of feces increased and SOC to a depth of 30 cm near permanent shades was 44.6 ± 2.0 Mg ha^{-1}, whereas farther away from shades was 40.0 ± 0.6 Mg ha^{-1} (Franzluebbers et al., 2000a).

3.4.1. Research evaluation and needs to characterize the effects of forage management and grazing on soil C sequestration

A great effort has been invested in forage management and grazing studies in the southeastern USA, but primarily on plant and animal responses, with relatively little effort focused on soil responses. There is a need to better characterize SOC under a wide variety of current and recommended forage and grazing management systems in different parts of the southeastern USA. Soil organic C responses to pasture management have the potential to be larger than those observed under cropping, because perennial grasses typically have a longer growing period, have a more extensive root system, and are less frequently disturbed. In contrast to rangeland, pasture establishment and renovation are more frequent and often not on the same parcel of land, creating different opportunities to gain and lose SOC. The much higher rate of SOC sequestration with grass establishment compared with no-tillage crop production suggests that pasture management in the southeastern USA deserves much greater attention for its role in SOC sequestration.

Many management issues concerning SOC sequestration in forage-based management systems remain unresolved, including the type of forage mixes that provide the greatest SOC accumulation, whether SOC sequestration and economic return to producers have similar guidelines, effect of soil type on management-induced soil response, and description of the biophysical limits under which cattle grazing systems might impart either negative or positive effects on C cycling and ecological function. Agricultural institutions across the southeastern USA simply need to set a priority on effectively integrating the efforts of soil, plant, and animal scientists to investigate multiple objectives on not only production issues, but also environmental quality issues on a broader scale.

4. Carbon dioxide, nitrous oxide, and methane fluxes

Carbon dioxide (CO_2) emission from soil is derived from both autotrophic and heterotrophic respiration. Maintenance of the plant energy system results in a significant release of CO_2 from roots embedded in soil. Heterotrophic respiration is derived from a wide variety of soil organisms that convert complex organic materials into simpler C compounds. Soil CO_2 flux as influenced by tillage management has been determined at several locations in the southeastern USA. During the 6th and 7th years of comparison between conventional- and no-tillage cropping in Georgia, soil CO_2 emission had (1) a peak of activity following mowing of cover crop in May, (2) rates strongly related to temperature, (3) a contribution from surface residues of 29 ± 19%, and (4) an overall higher rate under NT than under CT due to previous accumulation of SOC (Hendrix et al., 1988). During the 9th and 10th years of comparison between conventional- and no-tillage continuous cropping systems in Texas, soil CO_2 emission had (1) a peak in sorghum, wheat, and soybean cropping systems at different times of the year related to peak crop biomass, (2) rates related to soil temperature, soil water content, and time associated with primary inputs of crop residue and (3) an annual rate that was positively related to SOC concentration (Franzluebbers et al., 1995c). In this same tillage experiment under more diverse crop rotations, soil CO_2 emission was ~25% higher than under monoculture cropping systems as a result of ~40% greater C input via enhanced photosynthetic fixation (Franzluebbers et al., 1995d). On bermudagrass and sorghum fields in Texas, soil CO_2 emission following tillage was greatly stimulated for a few hours, but returned to values observed when untilled at the end of 24 h, which was attributable to physical release of stored CO_2 in the soil profile (Reicosky et al., 1997). In the 7th year of comparison between conventional- and no-tillage cropping in Alabama, soil CO_2 emission during the first 4 days of tillage following crimson clover cover crop desiccation was (1) three times greater when tilled than untilled, (2) stimulated by irrigation, and (3) not affected by traffic (Reicosky et al., 1999).

Nitrous oxide (N_2O) emission from soil is derived from denitrification and nitrification processes. Nitrification is an oxidative process carried out by a select group of organisms that convert ammonium to nitrate, in which a small amount of nitrous oxide can result (Tortoso and Hutchinson, 1990). Denitrification is a reductive process carried out by obligatory and facultative anaerobic bacteria that convert nitrate to either nitric oxide, nitrous oxide, or dinitrogen gas. The key process affecting nitrous oxide emission is denitrification, which is carried out by the population of denitrifying bacteria and is influenced by the level of oxygen present in soil, availability of nitrate as an electron acceptor, and availability of water-soluble organic C as an energy source. Therefore, nutrient-rich soils with abundant organic C under wet soil conditions would provide the most ideal conditions for denitrification to occur.

During the 5th and 6th years of comparison between conventional and NT cropping, potential N_2O emission from intact cores was measured on a monthly basis in Georgia (Groffman, 1984). At a depth of 0–5 cm, N_2O emission under NT was significantly greater on 6 of 10 dates than under CT, where SOC was 23 and 13 g kg^{-1}, respectively. At lower depths, opposite treatment effects occurred due to lower SOC under NT compared with CT.

Nitrous oxide emission from a bermudagrass field in Alabama during the summer averaged 4, 3, 2, and <1 kg N_2O–N ha^{-1} when supplied with fresh poultry litter, urea, composted poultry litter, and no N fertilizer, respectively (Thornton et al., 1998). Rates may have been low due to relatively dry soil conditions, in which water-filled pore space never exceeded 77%. During a 28-d laboratory incubation, N_2O emission from soil amended with poultry litter was 1 kg N_2O–N ha^{-1} at 58% water-filled pore space and 10 kg N_2O–N ha^{-1} at 90% water-filled pore space (Cabrera et al., 1994). During the first three years of removing cattle from a forested riparian area in Georgia, N_2O emission (24 kg N_2O–N ha^{-1} year^{-1}) was not different from that where cattle were not removed (Walker et al., 2002).

Confined animal feeding operations are becoming more widespread in the southeastern USA, and therefore, are potential sources of greenhouse gas emissions. From a swine production facility in Georgia, a variety of greenhouse gases were measured from the sludge layer of each of four lagoons during six periods in three different years (Harper et al., 2000). Emission of N_2O was only 4 kg ha^{-1} day^{-1} (6% of that of N_2 emission) and CO_2 emission was 8 kg ha^{-1} day^{-1}. Methane (CH_4) emission was high in the primary lagoon (126 kg ha^{-1} day^{-1}; 93% of lagoon system total) where dissolved oxygen was lowest.

Ruminant livestock, such as cattle and sheep, are a significant source of agricultural CH_4 production via enteric fermentation. USDA (2004) estimated that enteric fermentation represented ~70% of total CH_4 emission from agricultural sources in the USA. Harper et al. (1999) provided a summary of CH_4 emission values from cattle derived from a number of studies, resulting in a mean emission rate of 0.15 ± 0.08 kg CH_4 head^{-1} day^{-1}. With nearly 19 Mha of pasture land in the southeastern USA (Fig. 4) supporting ~12 million head of cattle (Fig. 6), the average cattle density in the region would be 0.62 head ha^{-1}. Therefore, CH_4 produced from grazing cattle could be calculated as 34 kg CH_4 ha^{-1} year^{-1}. With global warming potential of CH_4 21 times greater than that of CO_2, CH_4 emission from grazing cattle might contribute an atmospheric forcing of 0.37–1.20 Mg CO_2–C equivalent ha^{-1} year^{-1} (lower and upper end of mean ± one standard deviation). Since this estimate of greenhouse gas emission from enteric fermentation is similar to the estimate of SOC sequestration with pasture establishment (Table 8), whether cattle production systems in the southeastern USA might contribute to or mitigate greenhouse gas emissions would depend upon a number of specific management factors. Variation in total CH_4 emission from cattle production would be affected by a number of factors, including type and quality of forage, supplemental diet composition, rumen microfloral composition, stocking density, and animal breed, class, age, condition, and intake rate (Johnson and Johnson, 1995; Estermann et al., 2002).

4.1. Research evaluation and needs to characterize carbon dioxide, methane, and nitrous oxide fluxes

Data on CO_2, CH_4, and N_2O emissions from agricultural operations in the southeastern USA are very scarce. Soil CO_2 evolution is greatly enhanced immediately following inversion tillage (Reicosky et al., 1997, 1999), most likely due to physical release of accumulated soil-profile CO_2. However, in the long term following initial disturbance, most cropping systems managed with conservation tillage may actually release greater quantity of CO_2 than with CT, because of the accumulation of surface SOC (Hendrix et al., 1988; Franzluebbers et al., 1995c,d). Although increased cropping intensity can lead to a greater absolute rate of soil CO_2 evolution because of greater C fixation, similar or increased SOC sequestration per unit of C input results in net sequestration of SOC (Franzluebbers et al., 1998).

Much more work is needed in the region to characterize the fluxes of CH_4 and N_2O from crop and pasture lands, as well as from animal confinement operations that are abundant. The impacts of organic and inorganic fertilization of diverse cropping systems and pastures in the region on CH_4 and N_2O emissions remain relatively unknown. The effect of tillage management on these fluxes has also not been extensively investigated. How gas fluxes from the relatively fragmented agricultural landscape interact with potential sinks in adjacent forests in the region needs to be described. Calculations are needed of the relative greenhouse gas contributions from inorganic fertilizers versus land application of animal manures on a field, farm, and regional basis.

5. Recommendations for future research

This review of literature on greenhouse gas contributions from agricultural activities in the southeastern USA has highlighted (1) the growing wealth of information on SOC sequestration with conservation tillage of crop land and (2) the dearth of information on SOC sequestration and greenhouse gas emissions from pasture land. Some estimates of SOC sequestration in pastures indicate great potential for agricultural mitigation of greenhouse gas emissions. Studies are needed to evaluate the complete suite of greenhouse gas emissions, not just single response variables. More long-term studies (≥10 years) must urgently be developed to be able to obtain an appropriate steady-state perspective on these emissions. Development of studies will likely require a multidisciplinary approach so that the monetary cost of establishing and maintaining long-term research experiments can be spread across a wider group of collaborators in different institutions. More field, watershed, and regional studies are needed, but effective integration of results will require a sophisticated level of coordination to be able to obtain the most useful data. Effective mitigation of greenhouse gases on a regional scale will also require integration of resources among different sectors of the region, including agricultural, forestry, manufacturing, municipal, and energy enterprises.

Many key process-level research questions remain to be answered in the southeastern USA. Little is known about which agricultural management scenarios will capture the greatest amount of SOC and, at the same time, reduce emissions of N_2O and CH_4. How biological N fixation can contribute to greenhouse gas mitigation by increasing soil fertility, reducing the need for commercially produced fertilizer, sequestering SOC, and emitting N_2O should be investigated for a number of different symbiotic plant associations and crop management systems. How animal manure can be more effectively integrated into modern agricultural operations for efficient utilization of nutrients, effective long-term storage of organic C, and reduced trace gas emissions needs to be developed. Production, environmental, and political approaches to agriculture need to be developed in concert for more local and regional integration of crop and livestock operations so that agriculture in the southeastern USA becomes more productive, environmentally friendly, and profitable in order to meet the growing needs of the region and the world.

References

Agbenin, J.O., Goladi, J.T., 1997. Carbon, nitrogen and phosphorus dynamics under continuous cultivation as influenced by farmyard manure and inorganic fertilizers in the savanna of norther Nigeria. Agric. Ecosyst. Environ. 63, 17–24.

Bailey, R.G., 1995. Description of the Ecoregions of the United States. United States Department of Agriculture, 1391, 2nd ed. Forest Service. Misc. Publ., 108 pp.

Baker, S.H., 1987. Effects of tillage practices on cotton double cropped with wheat. Agron. J. 79, 513–516.

Bauer, P.J., Busscher, W.J., 1993. Effect of winter cover on soil moisture content in conventional and strip tillage cotton. In: Bollich, P.K. (Ed.), Proceedings of the 1993 Southern Conservative Tillage Conference for Sustainable Agriculture, Monroe, LA, pp. 8–10.

Beare, M.H., Hendrix, P.F., Coleman, D.C., 1994. Water-stable aggregates and organic matter fractions in conventional- and no-tillage soils. Soil Sci. Soc. Am. J. 58, 777–786.

Bishnoi, U.R., Mays, D., 2002. Tillage, weed control methods and row spacing affect soil properties and yield of grain sorghum and soybean. In: van Santen, E. (Ed.), Making Conservation Tillage Conventional: Building a Future on 25 Years of Research, Special Report No. 1. Alabama Agric. Expt. Stn., Auburn Univ., pp. 376–381.

Bhogal, A., Shepherd, M., 1997. Effect of poultry manure on the leaching of carbon from a sandy soil as a potential substrate for denitrification in the subsoil. J. Sci. Food Agric. 74, 313–322.

Boquet, D.J., Coco, A.B., 1993. Cotton yield and growth responses to tillage and cover crops on Sharkey clay. In: Bollich, P.K. (Ed.), Proceedings of the 1993 Southern Conservation Tillage Conference for Sustainable Agriculture, Monroe, LA, pp. 100–105.

Buntin, G.D., Raymer, P.D., Bednarz, C.W., Phillips, D.V., Baird, R.E., 2002. Winter crop, tillage, and planting date effects on double-crop cotton. Agron. J. 94, 273–280.

Burmester, C.H., Patterson, M.G., Reeves, D.W., 1993. No-till cotton growth characteristics and yield in Alabama. In: Bollich, P.K. (Ed.), Proceedings of the 1993 Southern Conservation Tillage Conference for Sustainable Agriculture, Monroe, LA, pp. 30–36.

Burmester, C.H., Reeves, D.W., Motta, A.C.V., 2002. Effect of crop rotation/tillage systems on cotton yield in the Tennessee Valley area of Alabama, 1980–2001. In: van Santen, E. (Ed.), Making Conservation Tillage Conventional: Building a Future on 25 Years of Research, Special Report No. 1. Alabama Agric. Expt. Stn., Auburn Univ., pp. 354–357.

Busscher, W.J., Bauer, P.J., 2003. Soil strength, cotton root growth and lint yield in a southeastern USA coastal loamy sand. Soil Tillage Res. 74, 151–159.

Cabrera, M.L., Chiang, S.C., Merka, W.C., Pancorbo, O.C., Thompson, S.A., 1994. Pelletizing and soil water effects on gaseous emissions from surface-applied poultry litter. Soil Sci. Soc. Am. J. 58, 807–811.

Cassel, D.K., Wagger, M.G., 1996. Residue management for irrigated maize grain and silage production. Soil Tillage Res. 39, 101–114.

Cheshire, J.M., Hargrove, W.L., Rothrock, C.S., Walker, M.E., 1985. Comparisons of conventional and no-tillage peanut production practices in central Georgia. In: Hargrove, W.L., Boswell, F.C., Langdale, G.W. (Eds.), Proceedings of the 1985 Southern Region No-Till Conference, Griffin, GA, pp. 82–86.

Christensen, B.T., 1988. Effects of animal manure and mineral fertilizer on the total carbon and nitrogen contents of soil size fractions. Biol. Fertil. Soils 5, 304–307.

CTIC, 2002. National Crop Residue Management Survey. Conservation Technology Information Center. http://www.ctic.purdue.edu/Core4/CT/ctsurvey/2002/RegionalSynopses.html.

Dabney, S.M., Murphree, C.E., Triplett, G.B., Grissinger, E.H., Meyer, L.D., Reinshmiedt, L.R., Rhoton, F.E., 1993. Conservation production systems for silty uplands. In: Bollich, P.K. (Ed.), Proceedings of the 1993 Southern Conservation Tillage Conference for Sustainable Agriculture, Monroe, LA, pp. 43–48.

Davidson, E.A., Ackerman, I.L., 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. Biogeochemistry 20, 161–193.

Delaney, D.P., Reeves, D.W., Monks, C.D., Patteson, M.G., Mullins, G.L., Gamble, B.E., 2002. Cover crops and tillage combinations for wide and ultra narrow row cotton. In: van Santen, E. (Ed.), Making Conservation Tillage Conventional: Building a Future on 25 Years of Research, Special Report No. 1. Alabama Agric. Expt. Stn., Auburn Univ., pp. 369–370.

Denton, H.P., Tyler, D.D., 2002. Making no-till ‘‘conventional’’ in Tennessee. In: van Santen, E. (Ed.), Making Conservation Tillage Conventional: Building a Future on 25 Years of Research, Special Report No. 1. Alabama Agric. Expt. Stn., Auburn Univ., pp. 53–58.

DeVane, E.H., Stelly, M., Burton, G.W., 1952. Effect of fertilization and management of different types of bermuda and bahia grass sods on the nitrogen and organic matter content of Tifton sandy loam. Agron. J. 44, 176–179.

Ding, G., Novak, J.M., Amarasiriwardena, D., Hunt, P.G., Xing, B., 2002. Soil organic matter characteristics as affected by tillage management. Soil Sci. Soc. Am. J. 66, 421–429.

Edwards, J.H., Thurlow, D.L., Eason, J.T., 1988. Influence of tillage and crop rotation on yields of corn, soybean, and wheat. Agron. J. 80, 76–80.

Edwards, J.H., Wood, C.W., Thurlow, D.L., Ruf, M.E., 1992. Tillage and crop rotation effects on fertility status of a Hapludult soil. Soil Sci. Soc. Am. J. 56, 1577–1582.

Elmore, C.D., Heatherly, L.G., 1988. Planting system and weed control effects on soybean grown on clay soil. Agron. J. 80, 818–821.

Endale, D.M., Cabrera, M.L., Steiner, J.L., Radcliffe, D.E., Vencill, W.K., Schomberg, H.H., Lohr, L., 2002. Impact of conservation tillage and nutrient management on soil water and yield of cotton fertilized with poultry litter or ammonium nitrate in the Georgia Piedmont. Soil Tillage Res. 66, 55–68.

Endale, D.M., Schomberg, H.H., Steiner, J.L., 2000. Long-term sediment yield and mitigation in a small Southern Piedmont watershed. Int. J. Sediment Res. 14, 60–68.

Estermann, B.L., Sutter, F., Schlegel, P.O., Erdin, D., Wettstein, H.-R., Kreuzer, M., 2002. Effect of calf age and dam on intake, energy expenditure, and excretion of nitrogen, phosphorus, and methane of beef cows with calves. J. Anim. Sci. 80, 1124–1134.

Feng, Y., Motta, A.C., Burmester, C.H., Reeves, D.W., van Santen, E., Osborne, J.A., 2002. Effects of tillage systems on soil microbial community structure under a continuous cotton cropping system. In: van Santen, E. (Ed.), Making Conservation Tillage Conventional: Building a Future on 25 Years of Research, Special Report No. 1. Alabama Agric. Expt. Stn., Auburn Univ., pp. 222–226.

Fesha, I.G., Shaw, J.N., Reeves, D.W., Wood, C.W., Feng, Y., Norfleet, M.L., van Santen, E., 2002. Land use effects on soil quality parameters for identical soil taxa. In: van Santen, E. (Ed.), Making Conservation Tillage Conventional: Building a Future on 25 Years of Research, Special Report No. 1. Alabama Agric. Expt. Stn., Auburn Univ., pp. 233–238.

Franzluebbers, A.J., 2002. Water infiltration and soil structure related to organic matter and its stratification with depth. Soil Tillage Res. 66, 197–205.

Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1994. Long-term changes in soil carbon and nitrogen pools in wheat management systems. Soil Sci. Soc. Am. J. 58, 1639–1645.

Franzluebbers, A.J., Hons, F.M., Saladino, V.A., 1995a. Sorghum, wheat and soybean production as affected by long-term tillage, crop sequence and fertilization. Plant Soil 173, 55–65.

Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1995b. Soil organic carbon, microbial biomass, and mineralizable carbon and nitrogen in sorghum. Soil Sci. Soc. Am. J. 59, 460–466.

Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1995c. Tillage and crop effects on seasonal dynamics of soil CO_2 evolution, water content, temperature, and bulk density. Appl. Soil Ecol. 2, 95–109.

Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1995d. Tillage-induced seasonal changes in soil physical properties affecting soil CO_2 evolution under intensive cropping. Soil Till. Res. 34, 41–60.

Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1998. In situ and potential CO_2 evolution from a fluventic Ustochrept in south-central Texas as affected by tillage and crop management. Soil Till. Res. 47, 303–308.

Franzluebbers, A.J., Langdale, G.W., Schomberg, H.H., 1999a. Soil carbon, nitrogen, and aggregation in response to type and frequency of tillage. Soil Sci. Soc. Am. J. 63, 349–355.

Franzluebbers, A.J., Nazih, N., Stuedemann, J.A., Fuhrmann, J.J., Schomberg, H.H., Hartel, P.G., 1999b. Soil carbon and nitrogen pools under low- and high-endophyte-infected tall fescue. Soil Sci. Soc. Am. J. 63, 1687–1694.

Franzluebbers, A.J., Steiner, J.L., 2002. Climatic influences on soil organic carbon storage with no tillage. In: Kimble, J.M., Lal, R., Follett, R.F. (Eds.), Agricultural Practices and Policies for Carbon Sequestration in Soil. Lewis Publ., Boca Raton, FL, pp. 71–86.

Franzluebbers, A.J., Stuedemann, J.A., Schomberg, H.H., 2000a. Spatial distribution of soil carbon and nitrogen pools under grazed tall fescue. Soil Sci. Soc. Am. J. 64, 635–639.

Franzluebbers, A.J., Stuedemann, J.A., Schomberg, H.H., Wilkinson, S.R., 2000b. Soil organic C and N pools under long-term pasture management in the Southern Piedmont USA. Soil Biol. Biochem. 32, 469–478.

Franzluebbers, A.J., Stuedemann, J.A., Wilkinson, S.R., 2001. Bermudagrass management in the Southern Piedmont USA. I. Soil and residue carbon and sulfur. Soil Sci. Soc. Am. J. 65, 834–841.

Frederick, J.R., Bauer, P.J., 1996. Winter wheat responses to surface and deep tillage on the southeastern Coastal Plain. Agron. J. 88, 829–833.

Gallaher, R.N., 1993. Cover crops and nitrogen management for no-tillage corn. In: Bollich, P.K. (Ed.), Proceedings of the 1993 Southern Conservation Tillage Conference for Sustainable Agriculture, Monroe, LA, pp. 81–84.

Giddens, J., 1957. Rate of loss of carbon from Georgia soils. Soil Sci. Soc. Proc. 21, 513–515.

Giddens, J., Adams, W.E., Dawson, R.N., 1971. Nitrogen accumulation in fescuegrass sod. Agron. J. 63, 451–454.

Gordon, W.B., Rickerl, D.H., Touchton, J.T., 1990. Effects of nitrogen, dicyandiamide, and tillage on cotton nitrogen concentration and yield. Agron. J. 82, 597–600.

Govi, M., Francioso, O., Ciavatta, C., Sequi, P., 1992. Influence of long-term residue and fertilizer applications on soil humic substances: a case study by electrofocusing. Soil Sci. 154, 8–13.

Groffman, P.M., 1984. Nitrification and denitrification in conventional and no-tillage soils. Soil Sci. Soc. Am. J. 49, 329–334.

Groffman, P.M., Hendrix, P.F., Crossley, D.A., 1987. Nitrogen dynamics in conventional and no-tillage agroecosystems with inorganic fertilizer or legume nitrogen inputs. Plant Soil 97, 315–333.

Gupta, A.P., Narwal, R.P., Antil, R.S., Dev, S., 1992. Sustaining soil fertility with organic-C, N, P, and K by using farmyard manure and fertilizer-N in a semiarid zone: a long-term study. Arid Soil Res. Rehabil. 6, 243–251.

Harden, J.W., Sharpe, J.M., Parton, W.J., Ojima, D.S., Fries, T.L., Huntington, T.G., Dabney, S.M., 1999a. Dynamic replacement and loss of soil carbon on eroding cropland. Global Biogeochem. Cycles 13, 885–901.

Hargrove, W.L., 1985. Influence of tillage on nutrient uptake and yield of corn. Agron. J. 77, 763–768.

Hargrove, W.L., Cummins, D.G., Cordonnier, M.J., Day, J.L., 1985. Influence of tillage on performance of soybean cultivars. In: Hargrove, W.L., Boswell, F.C., Langdale, G.W. (Eds.), Proceedings of the 1985 Southern Region No-Till Conference, Griffin, GA, pp. 35–39.

Harden, J.W., Sharpe, J.M., Parton, W.J., Ojima, D.S., Fries, T.L., Huntington, T.G., Dabney, S.M., 1999b. Dynamic replacement and loss of soil carbon on eroding cropland. Global Biogeochem. Cycles 13, 885–901.

Harper, L.A., Denmead, O.T., Freney, J.R., Byers, F.M., 1999. Direct measurements of methane emissions from grazing and feedlot cattle. J. Anim. Sci. 77, 1392–1401.

Harper, L.A., Sharpe, R.R., Parkin, T.B., 2000. Gaseous nitrogen emissions from anaerobic swine lagoons: Ammonia, nitrous oxide, and dinitrogen gas. J. Environ. Qual. 29, 1356–1365.

Hendrix, P.F., Franzluebbers, A.J., McCracken, D.V., 1998. Management effects on C accumulation and loss in soils of the southern Appalachian Piedmont of Georgia. Soil Till. Res. 47, 245–251.

Hendrix, P.F., Han, C.-R., Groffman, P.M., 1988. Soil respiration in conventional and no-tillage agroecosystems under different winter cover crop rotations. Soil Till. Res. 12, 135–148.

Hu, S., Coleman, D.C., Beare, M.H., Hendrix, P.F., 1995. Soil carbohydrates in aggrading and degrading agroecosystems: Influences of fungi and aggregates. Agric. Ecosys. Environ. 54, 77–88.

Hu, S., Coleman, D.C., Carroll, C.R., Hendrix, P.F., Beare, M.H., 1997. Labile soil carbon pools in subtropical forest and agricultural ecosystems as influenced by management practices and vegetation types. Agric. Ecosys. Environ. 65, 69–78.

Hunt, P.G., Karlen, D.L., Matheny, T.A., Quisenberry, V.L., 1996. Changes in carbon content of a Norfolk loamy sand after 14 years of conservation or conventional tillage. J. Soil Water Conserv. 51, 255–258.

Hunt, P.G., Matheny, T.A., Wollum, A.G., 1985. *Rhizobium japonicum* nodular occupancy, nitrogen accumulation, and yield for determinate soybean under conservation and conventional tillage. Agron. J. 77, 579–584.

Hutchinson, R.L., Brown, R.A., Leonard, B.R., Kennedy, C.W., 1993. Effects of tillage systems and winter cover crops on yield and maturity of cotton on a loess soil in northeast Louisiana. In: Bollich, P.K. (Ed.), Proceedings of the 1993 Southern Conservation Tillage Conference for Sustainable Agriculture, Monroe, LA, pp. 85–91.

IPCC (Intergovernmental Panel on Climate Change), 1997. Guidelines for National Greenhouse Gas Inventories, Chapter 4, Agiculture: Nitrous oxide from agricultural soils and manure management. Org. Econ. Coop. Develop., Paris, France.

Islam, K.R., Weil, R.R., 2000. Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management. J. Soil Water Conserv. 55, 69–78.

Iversen, K.W., 2002.In: 25 Years: Proceedings of the Southern Conservation Tillage Conference for Sustainable Agriculture, 1978 to 2002. CD-ROM.

Izaurralde, R.C., McGill, W.B., Bryden, A., Graham, S., Ward, M., Dickey, P., 1998. Scientific challenges in developing a plan to predict and verify carbon storage in Canadian Prairie soils. In: Lal, R., et al. (Eds.), Management of Carbon Sequestration in Soil. CRC Press, Boca Raton, FL, pp. 433–446.

Jackson, W.A., Wilkinson, S.R., Leonard, R.A., 1977. Land disposal of broiler litter: changes in concentration of chloride, nitrate nitrogen, and organic matter in a Cecil sandy loam. J. Environ. Qual. 6, 58–62.

Johnson, K.A., Johnson, D.E., 1995. Methane emissions from cattle. J. Anim. Sci. 73, 2483–2492.

Johnson, W.C., Brenneman, T.B., Baker, S.H., Johnson, A.V., Sumner, D.R., Mullinix, B.G., 2001. Tillage and pest management considerations in a peanut-cotton rotation in the southeastern Coastal Plain. Agron. J. 93, 570–576.

Jones, L.S., Anderson, O.E., Stavy, S.V., 1966. Some effects of sod-based rotations upon soil properties, Georgia Agric. Expt. Stat. Bull., No. 166.

Jordan, D.L., Barnes, J.S., Bogle, C.R., Brandenburg, R.L., Bailey, J.E., Johnson, P.D., Culpepper, A.S., 2003. Peanut response to cultivar selection, digging date, and tillage intensity. Agron. J. 95, 380–385.

Jordan, D.L., Barnes, J.S., Bogle, C.R., Naderman, G.C., Roberson, G.T., Johnson, P.D., 2001. Peanut response to tillage and fertilization. Agron. J. 93, 1125–1130.

Kapkiyai, J.J., Karanja, N.K., Qureshi, J.N., Smithson, P.C., Woomer, P.L., 1999. Soil organic matter and nutrient dynamics in a Kenyan nitisol under long-term fertilizer and organic input management. Soil Biol. Biochem. 31, 1773–1782.

Karlen, D.L., Berti, W.R., Hunt, P.G., Matheny, T.A., 1989. Soil-test values after eight years of tillage research on a Norfolk loamy sand. Commun. Soil Sci. Plant Anal. 20, 1413–1426.

Karlen, D.L., Gooden, D.T., 1987. Tillage systems for wheat production in the southeastern Coastal Plains. Agron. J. 79, 582–587.

Karlen, D.L., Sojka, R.E., 1985. Hybrid and irrigation effects on conservation tillage corn in the Coastal Plain. Agron. J. 77, 561–567.

Kingery, W.L., Wood, C.W., Delaney, D.P., Williams, J.C., Mullins, G.L., 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. J. Environ. Qual. 23, 139–147.

Kingery, W.L., Wood, C.W., Williams, J.C., 1996. Tillage and amendment effects on soil carbon and nitrogen mineralization and phosphorus release. Soil Tillage Res. 37, 239–250.

Lal, R., Kimble, J.M., Follett, R.F., Cole, C.V., 1998. The Potential of US Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. Ann Arbor Press, Chelsea, MI, 128 pp..

Langdale, G.W., Hargrove, W.L., Giddens, J., 1984. Residue management in double-crop conservation tillage systems. Agron. J. 76, 689–694.

Langdale, G.W., Wilson, R.L., Bruce, R.R., 1990. Cropping frequencies to sustain long-term conservation tillage systems. Soil Sci. Soc. Am. J. 54, 193–198.

Laws, W.D., Evans, D.D., 1949. The effects of long-time cultivation on some physical and chemical properties of two rendzina soils. Soil Sci. Soc. Am. Proc. 13, 15–19.

Lee, R.D., Reeves, D.W., Pippin, R., Walker, J., 2002. High-residue conservation system for corn and cotton in Georgia. In: van Santen, E. (Ed.), Making Conservation Tillage Conventional: Building a Future on 25 Years of Research, Special Report No. 1. Alabama Agric. Expt. Stn., Auburn Univ., pp. 327–330.

Lowrance, R., Williams, R.G., 1988. Carbon movement in runoff and erosion under simulated rainfall conditions. Soil Sci. Soc. Am. J. 52, 1445–1448.

Ma, Z., Wood, C.W., Bransby, D.I., 2000. Soil management impacts on soil carbon sequestration by switchgrass. Biomass Bioenergy 18, 469–477.

Mann, L.K., 1986. Changes in soil carbon storage after cultivation. Soil Sci. 142, 279–288.

Marois, J.J., Wright, D.L., 2003. Effect of tillage system, phorate, and cultivar on tomato spotted wilt of peanut. Agron. J. 95, 386–389.

McCarty, G.W., Lyssenko, N.N., Starr, J.L., 1998. Short-term changes in soil carbon and nitrogen pools during tillage management transition. Soil Sci. Soc. Am. J. 62, 1564–1571.

McCarty, G.W., Meisinger, J.J., 1997. Effects of N fertilizer treatments on biologically active N pools in soils under plow and no tillage. Biol. Fertil. Soils 24, 406–412.

McCracken, R.J., 1959. Certain properties of selected southeastern United States soils and mineralogical procedures for their study. Southern Regional Bulletin 61. Virginia Agric. Expt. Stat, Virginia Polytechnic Inst., Blacksburg, VA, 146 pp.

McGregor, K.C., Greer, J.D., Gurley, G.E., 1975. Erosion control with no-tillage cropping practice. Trans. ASAE 18, 918–920.

Meisinger, J.J., Bandel, V.A., Stanford, G., Legg, J.O., 1985. Nitrogen utilization of corn under minimal tillage and moldboard plow tillage. I. Four-year results using labeled N fertilizer on an Atlantic Coastal Plain soil. Agron. J. 77, 602–611.

Mitchell, C.C., Entry, J.A., 1998. Soil C, N and crop yields in Alabama's long-term 'Old Rotation' cotton experiment. Soil Tillage Res. 47, 331–338.

Mitchell, C.C., Reeves, D.W., Delaney, D., 2002. Conservation tillage in Alabama's "Old Rotation". In: van Santen, E. (Ed.), Making Conservation Tillage Conventional: Building a Future on 25 Years of Research, Special Report No. 1. Alabama Agric. Expt. Stn., Auburn Univ., pp. 30–35.

Moore, P.A., Daniel, T.C., Sharpley, A.N., Wood, C.W., 1995. Poultry manure management: Environmentally sound options. J. Soil Water Conserv. 50, 321–327.

Motta, A.C.V., Reeves, D.W., Touchton, J.T., 2002. Tillage intensity effects on chemical indicators of soil quality in two Coastal Plain soils. Commun. Soil Sci. Plant Anal. 33, 913–932.

Mullins, G.L., Alley, S.E., Reeves, D.W., 1998. Tropical maize response to nitrogen and starter fertilizer under strip and conventional tillage systems in southern Alabama. Soil Tillage Res. 45, 1–15.

Mutchler, C.K., McDowell, L.L., Johnson, J.R., 1985. Erosion from reduced-till cotton. In: Hargrove, W.L., Boswell, F.C., Langdale, G.W. (Eds.), Proceedings of the 1985 Southern Region No-Till Conference, Griffin, GA, pp. 156–158.

Naderman, G.C., Brock, B.G., Reddy, G.B., Raczkowski, C.W., 2004. Six years of continuous conservation tillage at the Center for Environmental Farming Systems (CEFS). Part I. Impacts on soil bulk density and carbon content for differing soils and crop rotations. Ann. Mtg. Soil Sci. Soc. North Carolina, 21 January, Raleigh, NC.

Nelson, L.R., Gallaher, R.N., Holmes, M.R., Bruce, R.R., 1977. Corn forage production in no-till and conventional tillage double-cropping systems. Agron. J. 69, 635–638.

NeSmith, D.S., Hargrove, W.L., Radcliffe, D.E., Tollner, E.W., Arioglu, H.H., 1987. Tillage and residue management effects on properties of an Ultisol and double-cropped soybean production. Agron. J. 79, 570–576.

Novak, J.M., Watts, D.W., Hunt, P.G., 1996. Long-term tillage effects on atrazine and fluometuron sorption in Coastal Plain soils. Agric. Ecosys. Environ. 60, 165–173.

Nyakatawa, E.Z., Reddy, K.C., 2002. Conservation tillage and poultry litter effects on cotton and corn yields: Five year results. In: van Santen, E. (Ed.), Making Conservation Tillage Conventional: Building a Future on 25 Years of Research, Special Report No. 1. Alabama Agric. Expt. Stn., Auburn Univ., pp. 142–147.

Nyakatawa, E.Z., Reddy, K.C., Brown, G.F., 2001. Residual effect of poultry litter applied to cotton in conservation tillage systems on succeeding rye and corn. Field Crops Res. 71, 159–171.

Nyakatawa, E.Z., Reddy, K.C., Mays, D.A., 2000. Tillage, cover cropping, and poultry litter effects on cotton: II. Growth and yield parameters. Agron. J. 92, 1000–1007.

Parsch, L.D., Keisling, T.C., Sauer, P.A., Oliver, L.R., Crabtree, N.S., 2001. Economic analysis of conservation and conventional tillage cropping systems on clayey soil in eastern Arkansas. Agron. J. 93, 1296–1304.

Pettigrew, W.T., Jones, M.A., 2001. Cotton growth and no-till production in the lower Mississippi river valley alluvial flood plain. Agron. J. 93, 1398–1404.

Popp, M.P., Keisling, T.C., McNew, R.W., Oliver, L.R., Dillon, C.R., Wallace, D.M., 2002. Planting date, cultivar, and tillage system effects on dryland soybean production. Agron. J. 94, 81–88.

Potter, K.N., Chichester, F.W., 1993. Physical and chemical properties of a Vertisol with continuous controlled-traffic, no-till management. Trans. ASAE 36, 95–99.

Potter, K.N., Daniel, J.A., Altom, W., Torbert, H.A., 2001. Stocking rate effect on soil carbon and nitrogen in degraded soils. J. Soil Water Conserv. 56, 233–236.

Potter, K.N., Torbert, H.A., Johnson, H.B., Tischler, C.R., 1999. Carbon storage after long-term grass establishment on degraded soils. Soil Sci. 164, 718–725.

Potter, K.N., Torbert, H.A., Jones, O.R., Matocha, J.E., Morrison Jr., J.E., Unger, P.W., 1998. Distribution and amount of soil organic C in long-term management systems in Texas. Soil Tillage Res. 47, 309–321.

Raczkowski, C.W., Reddy, G.B., Reyes, M.R., Gayle, G.A., Busscher, W., Bauer, P., Brock, B., 2002. No-tillage performance on a Piedmont soil. In: van Santen, E. (Ed.), Making Conservation Tillage Conventional: Building a Future on 25 Years of Research, Special Report No. 1. Alabama Agric. Expt. Stn., Auburn Univ., pp. 273–276.

Raun, W.R., Johnson, G.V., Phillips, S.B., Westerman, R.L., 1998. Effect of long-term N fertilization on soil organic C and total N in continuous wheat under conventional tillage in Oklahoma. Soil Tillage Res. 47, 323–330.

Reader, J., Craft, C., 1999. Comparison of wetland structure and function on grazed and ungrazed salt marshes. J. Elisha Mitchell Sci. Soc. 115, 236–249.

Reeves, D.W., 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil Tillage Res. 43, 131–167.

Reeves, D.W., Delaney, D.P., 2002. Conservation rotations for cotton production and carbon storage.. In: van Santen, E. (Ed.), Making Conservation Tillage Conventional: Building a Future on 25 Years of Research, Special Report No. 1. Alabama Agric. Expt. Stn., Auburn Univ., pp. 344–348.

Reicosky, D.C., Dugas, W.A., Torbert, H.A., 1997. Tillage-induced soil carbon dioxide loss from different cropping systems. Soil Tillage Res. 41, 105–118.

Reicosky, D.C., Reeves, D.W., Prior, S.A., Runion, G.B., Rogers, H.H., Raper, R.L., 1999. Effects of residue management and controlled traffic on carbon dioxide and water loss. Soil Tillage Res. 52, 153–165.

Rhoton, F.E., 2002. Influence of time on soil response to no-till practices. Soil Sci. Soc. Am. J. 64, 700–709.

Rhoton, F.E., Bruce, R.R., Buehring, N.W., Elkins, G.B., Langdale, G.W., Tyler, D.D., 1993. Chemical and physical characteristics of four soil types under conventional and no-tillage systems. Soil Tillage Res. 28, 51–61.

Rhoton, F.E., Shipitalo, M.J., Lindbo, D.L., 2002. Runoff and soil loss from midwestern and southeastern US silt loam soils as affected by tillage practice and soil organic matter content. Soil Tillage Res. 66, 1–11.

Rhoton, F.E., Tyler, D.D., 1990. Erosion-induced changes in the properties of a fragipan soil. Soil Sci. Soc. Am. J. 54, 223–228.

Richardson, C.W., King, K.W., 1995. Erosion and nutrient losses from zero tillage on a clay soil. J. Agric. Eng. Res. 61, 81–86.

Sainju, U.M., Singh, B.P., 2001. Tillage, cover crop, and kill-planting date effects on corn yield and soil nitrogen. Agron. J. 93, 878–886.

Sainju, U.M., Singh, B.P., Whitehead, W.F., 2002a. Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. Soil Tillage Res. 63, 167–179.

Salinas-Garcia, J.R., Hons, F.M., Matocha, J.E., 1997. Long-term effects of tillage and fertilization on soil organic matter dynamics. Soil Sci. Soc. Am. J. 61, 152–159.

Sanderson, M.A., Reed, R.L., Ocumpaugh, W.R., Hussey, M.A., van Esbroeck, G., Read, J.C., Tischler, C.R., Hons, F.M., 1999. Switchgrass cultivars and germplasm for biomass feedstock production in Texas. Bioresour. Technol. 67, 209–219.

Schnabel, R.R., Franzluebbers, A.J., Stout, W.L., Sanderson, M.A., Stuedemann, J.A., 2001. The effects of pasture management practices. In: Follett, R.F., Kimble, J.M., Lal, R. (Eds.), The Potential of US Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. CRC Press, Boca Raton, FL, pp. 291–322.

Schomberg, H.H., Langdale, G.W., Franzluebbers, A.J., Lamb, M.C., 2003. Comparison of tillage type and frequencies for cotton on Southern Piedmont soils. Agron. J. 95, 1281–1287.

Schreiber, J.D., McGregor, K.C., 1979. The transport and oxygen demand of organic carbon released to runoff from crop residues. Prog. Water Technol. 11, 253–261.

Schwab, E.B., Reeves, D.W., Burmester, C.H., Raper, R.L., 2002. Conservation tillage systems for cotton in the Tennessee Valley. Soil Sci. Soc. Am. J. 66, 569–577.

Sharpley, A.N., Smith, S.J., Bain, W.R., 1993. Nitrogen and phosphorus fate from long-term poultry litter applications to Oklahoma soils. Soil Sci. Soc. Am. J. 57, 1131–1137.

Siri-Prieto, G., Reeves, D.W., Shaw, J.N., Mitchell, C.C., 2002. Impact of conservation tillage on soil carbon in the 'Old Rotation'. In: van Santen, E. (Ed.), Making Conservation Tillage Conventional: Building a Future on 25 Years of Research, Special Report No. 1. Alabama Agric. Expt. Stn., Auburn Univ., pp. 277–282.

Smart, J.R., Bradford, J.M., 1999. Conservation tillage corn production for a semiarid, subtropical environment. Agron. J. 91, 116–121.

Stuedemann, J.A., Hoveland, C.S., 1988. Fescue endophyte: history and impact on animal agriculture. J. Prod. Agric. 1, 39–44.

Thornton, F.C., Shurpali, N.J., Bock, B.R., Reddy, K.C., 1998. N_2O and NO emissions from poultry litter and urea applications to bermuda grass. Atmos. Environ. 32, 1623–1630.

Thurlow, D.L., Edwards, J.H., Gazaway, W., Eason, J.T., 1985. Influence of tillage and crop rotation on soybean yields and cyst nematode population. In: Hargrove, W.L., Boswell, F.C., Langdale, G.W. (Eds.), Proceedings of the 1985 Southern Region No-Till Conference, Griffin, GA, pp. 45–49.

Torbert, H.A., Potter, K.N., Morrison, J.E., 2001. Tillage system, fertilizer nitrogen rate, and timing effect on corn yields in the Texas Blackland Prairie. Agron. J. 93, 1119–1124.

Torbert, H.A., Prior, S.A., Runion, G.B., 2004. Impact of the return to cultivation on carbon (C) sequestration. J. Soil Water Conserv. 59, 1–8.

Tortoso, A.C., Hutchinson, G.L., 1990. Contributions of autotrophic and heterotrophic nitrifiers to soil NO and N_2O emissions. Appl. Environ. Microbiol. 56, 1799–1805.

Trimble, S.W., 1974. Man-Induced Soil Erosion on the Southern Piedmont, 1700–1970. Soil Conserv. Soc. Am., Ames IA., 180 p.

Triplett, G.B., Dabney, S.M., Siefker, J.H., 1996. Tillage systems for cotton on silty upland soils. Agron. J. 88, 507–512.

Triplett, G.B., Robinson, J.R.C., Dabney, S.M., 2002. A whole-farm economic analysis of no-tillage and tilled cropping systems. In: van Santen, E. (Ed.), Making Conservation Tillage Conventional: Building a Future on 25 Years of Research, Special Report No. 1. Alabama Agric. Expt. Stn., Auburn Univ., pp. 48–52.

Truman, C.C., Reeves, D.W., Shaw, J.N., Motta, A.C., Burmester, C.H., Raper, R.L., Schwab, E.B., 2003. Tillage impacts on soil property, runoff, and soil loss variations from a Rhodic Paleudult under simulated rainfall. J. Soil Water Conserv. 58, 258–267.

USDA, 2004. US Agriculture and Forestry Greenhouse Gas Inventory: 1990–2001. Tech. Bull. No. 1907. Global Change Program Office, Office Chief Economist, United States Department Agriculture, 164 pp.

USDA-NASS, 1997. Census of Agriculture, vol. 1, Geographic Area Series, U.S. Dept. Agric., National Agric. Stat. Serv., Washington, DC. CD-ROM.

USDA-NRCS, 1997. Soil Organic Carbon. United States Department of Agriculutre, Natural Resources Conservation Service, Soil Survey Division, World Soil Resources, Washington, DC, 1997. Available at http://www.nrcs.usda.gov/technical/use/worldsoils/mapindex/soc.html. Verified 9 September 2004.

USDA-SCS, 1981. Land resource regions and major land resource areas of the United States, Agriculture Handbook 296. Washington, DC.

VandenBygaart, A.J., Gregorich, E.G., Angers, D.A., 2003. Influence of agricultural management on soil organic carbon: a compendium and assessment of Canadian studies. Can. J. Soil Sci. 83, 363–380.

Wagger, M.G., Denton, H.P., 1989. Tillage effects on grain yields in a wheat, double-crop soybean, and corn rotation. Agron. J. 81, 493–498.

Wagger, M.G., Denton, H.P., 1992. Crop and tillage rotations: grain yield, residue cover, and soil water. Soil Sci. Soc. Am. J. 56, 1233–1237.

Walker, J.T., Geron, C.D., Vose, J.M., Swank, W.T., 2002. Nitrogen trace gas emissions from a riparian ecosystem in southern Appalachia. Chemosphere 49, 1389–1398.

Webster, C.P., Goulding, K.W.T., 1989. Influence of soil carbon content on denitrification from fallow land during autumn. J. Sci. Food Agric. 49, 131–142.

Weil, R.R., Benedetto, P.W., Sikora, L.J., Bandel, V.A., 1988. Influence of tillage practices on phosphorus distribution and forms in three Ultisols. Agron. J. 80, 503–509.

Weil, R.R., Kroontje, W., 1979. Organic matter decomposition in a soil heavily amended with poultry manure. J. Envrion. Qual. 8, 584–588.

Weil, R.R., Lowell, K.A., Shade, H.M., 1993. Effects of intensity of agronomic practices on a soil ecosystem. Am. J. Altern. Agric. 8, 5–14.

Wesley, R.A., Heatherly, L.G., Pringle, H.C., Tupper, G.R., 1988. Seedbed tillage and irrigation effects on yield of mono- and doublecrop soybean and wheat on a silt loam. Agron. J. 80, 139–143.

West, T.O., Marland, G., 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agric. Ecosyst. Environ. 91, 217–232.

West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. Soil Sci. Soc. Am. J. 66, 1930–1946.

Westerman, R.L., Boman, R.K., Raun, W.R., Johnson, G.V., 1994. Ammonium and nitrate nitrogen in soil profiles of long-term winter wheat fertilization experiments. Agron. J. 86, 94–99.

Wiatrak, P.J., Wright, D.L., Pudelko, J., Koziara, W., 2002. Influence of nitrogen and tillage on cotton. In: van Santen, E. (Ed.), Making Conservation Tillage Conventional: Building a Future on 25 Years of Research, Special Report No. 1. Alabama Agric. Expt. Stn., Auburn Univ., pp. 131–135.

Wood, B.H., Wood, C.W., Yoo, K.H., Yoon, K.S., Delaney, D.P., 1996. Nutrient accumulation and nitrate leaching under broiler litter amended corn fields. Commun. Soil Sci. Plant Anal. 27, 2875–2894.

Wright, D.L., Teare, I.D., 1993. No-till vs. conventional tillage for peanut vs. row spacing and irrigation. In: Bollich, P.K. (Ed.), Proceedings of the 1993 Southern Conservation Tillage Conference for Sustainable Agriculture, Monroe, LA, pp. 49–53.